THE DEVELOPMENT OF MATERIAL-ADAPTED STRUCTURAL FORM

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ABSTRACT
ENGLISH

New structural materials can potentially change the technics and economics of the building and construction industry in a profound way. It is important to identify applications and develop forms that exploit a material's unique properties. The developer of a material can use the knowledge of how materials such as steel and reinforced concrete were first introduced to advance the development and application of new materials today. This project examines *why* structural forms have evolved as they have and what *influences* the process of creating form, or *form-finding*. The purpose of this analysis is to aid the development of structural forms that make the most efficient use of material and take advantage of a material's processing and constructive attributes. Such forms are called *material-adapted*.

This thesis is based on the general history of structural materials used in construction. This research is summarized in six appended case studies that comprise the data of the thesis. The research has extended well beyond these case studies; some of this data is included in the main text.

The research showed that the influences on form-finding are: *Function*; *Material Properties*; *Processing Technologies*; *Connection Technology*; *Construction Process*; *Economics*; *Socio-Political Factors*; *Knowledge; and Technological Thought*. A Form-Finding Influence Interaction Model summarizes the inter-relationships of these influences.

It was first assumed that material-adapted form is determined by material properties alone. Further research showed this untrue. The hypothesis of this thesis is that *material properties do not unilaterally determine material-adapted structural form*. This statement is true because the *nature* of a material is a function of its properties and its processing and constructive attributes. A material's processing and constructive attributes are dependent on technology and organizational systems that are not specific to the material. It was further hypothesized that new materials are first used substitutionally in forms and applications of known materials. This concept was found to be misleading and untrue for a number of materials.

The knowledge of this thesis was used to examine the current development of fiber reinforced polymer composite materials. It is shown that a material's development can be analyzed not only by the aforementioned influences, but also by characteristics of other material developments. This information is used to suggest how these materials might develop in the future.

key words: structural materials ° properties ° form-finding ° material-adapted form

RÉSUMÉ
FRANÇAIS

Les nouveaux matériaux structuraux sont en mesure d’apporter de profonds changements dans les techniques et l’économie de l’industrie de la construction. De nos jours, le concepteur d'un nouveau matériau pourra se baser, pour son développement, sur les connaissances acquises dans le cadre des premières applications et utilisations de matériaux tels que l’acier et le béton armé. La présente étude analyse les causes ayant abouti aux formes structurelles développées et les facteurs ayant influencés le processus de création de cette forme ou de la « forme recherchée ». L’objectif de cette analyse est de concevoir un système d’aide au développement de formes structurelles dites « adaptées au matériau » tirant avantage des caractéristiques constructives et de fabrication du matériau.

Cette thèse est basée sur l’historique de l’évolution des matériaux de construction. Les connaissances sont résumées dans les six études de cas annexées. La recherche est allée audelà de celles-ci et certaines données sont incluses dans le rapport principal.

L‘étude démontre que les facteurs influençant la « forme recherchée » sont : la fonction, les propriétés du matériau, les technologies de production, les techniques de connexion, les procédés de construction, l’économie, les facteurs sociopolitiques, le savoir et les pensées technologiques. Un modèle d’interaction des facteurs d’influence pour la « forme recherchée » a été développé et résume les corrélations entre ces divers facteurs d’influence.

Initialement il a été avancé que la « forme adaptée au matériau » était déterminée par les seules propriétés intrinsèques du matériau. Des recherches successives ont démontré que cette supposition était inexacte. L’hypothèse présentée dans la thèse tend à confirmer que les propriétés du matériau ne déterminent pas de manière unilatérale la forme dite « adaptée au matériau ». Ceci est vrai, puisque la nature d’un matériau est fonction non seulement de ses propriétés mais aussi de ses caractéristiques constructives et de fabrication. Ces dernières dépendent de la technologie et des systèmes d’organisation, paramètres non spécifiques au matériau. S'agissant de l'hypothèse qui sous-tend que les nouveaux matériaux ont initialement été utilisés comme matériaux de substitution sous les formes et applications propres aux matériaux existants, il s'est avéré qu'elle n'est pas applicable à tous les matériaux.

Les enseignements tirés de cette thèse permettent d’examiner l’évolution du développement actuel des matériaux composites renforcés par des fibres. Il a été démontré que le développement d’un matériau peut être analysé non seulement à travers les facteurs d’influence précédemment mentionnés, mais aussi à travers les caractéristiques de développements d’autres matériaux. Ces informations sont susceptibles d’agir sur le possible futur développement des ces matériaux.

mots clés: matériaux structuraux ° propriétés ° forme recherchée ° forme adaptée au matériau

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PART I: THESIS

INTRODUCTION

01

1.1 The Problem

This project began with the observation that a structural material newly introduced into the building industry is likely utilized as a replacement to and in the shape of established materials.[1] The Greek Doric-style of architecture clearly exhibits details that are typical of wood construction, reinforcing the proposition that the stone temples of Greek antiquity derive from a timber building system.[2] (**Appendix A-01, p.A.4, Figs. 2, 3, and 4)** The Romans are the first civilization to exploit the arch, a form more appropriate to stone's strength properties than is its use as a beam.

Abraham Darby, Jr., an English iron founder, built Ironbridge, the first all-cast-iron bridge in the world, over the Severn River at Coalbrookdale, England, in 1779. This bridge has a semi-circular arch form; a characteristic of stone arches, and has connections typical of timber construction. (**Appendix A-02, p.A.41, Fig. 17; Fig. 3.10, top-center**) The first iron beams were not fabricated in England until 1796.

Around the turn of the twentieth century, reinforced concrete building systems were characterized by a hierarchical structure of column, beam, floor beam, and floor slab. The form of this system is typical iron or wood frame construction. (**Appendix A-05, p.A.243, Fig. 11**) The flat slab was invented in the first decade of the twentieth century. It introduced a two-way plate system to structural design.

These examples illustrate the hypothesis that structural materials are first used substitutionally, in familiar forms characteristic of known materials, before they are used in forms that best exploit their material properties. It is reasonable that new materials are used substitutionally because in this way developers of new materials can compare the behavioral characteristics of the new material against a known material.

When this project began, I assumed that the *substitution phase* of material development must be overcome for new materials to be successfully integrated into the market. Simple material substitution would lead to inefficient use of advantageous properties and, therefore, be an uneconomical application of the new material. The success of a new building material requires the development of so-called *material-adapted structural forms* that exploit a material's unique properties. However, my research has shown that the substitution phase does not typically occur when a new material is first introduced; rather, if it does occur, it happens in a later stage of material development when the material is in transition from being

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[1] Keller.

[2] **Ref. Appendix A-01**.

classed as new, novel, or conventional. Nevertheless, the initial perception of a material's development cycle led to the question:

- *Why have structural materials developed as they have?*

Today, fiber reinforced polymer composites (FRP), are considered novel structural materials for construction applications. Composites offer limited, if any, economic benefits because of processing costs. The only practical forms of FRP for all-composite construction are prismatic shapes produced by the pultrusion process. This process can make open or closed section forms – much like aluminum's extrusion process. Standard FRP pultruded products have forms identical to those produced from steel, such as angles, rounds, tubes, and I-sections. It seems incongruous that a material composed of linear fibers, held together by a polymer matrix material, should be used in the same forms as an isotropic metal.

I initially assumed that the 'traditional' materials are used today in material-adapted ways. Therefore, it followed that FRP is currently used substitutionally for steel. If this was the case, then two questions arise:

- *How do materials transcend the substitution phase to the status of being material-adapted?*
- *Can something useful be learned from the historical development of established structural materials to encourage the development of material-adapted forms of new materials today?*

To advance the development and application of a new material, today's designers can benefit from knowing how materials, such as steel and reinforced concrete, were first introduced. This project was conceived to analyze *why* structural forms have evolved as they have and determine what influences the process of creating form, or *form-finding*.

1.2 The Objective

The objective of this thesis is to answer the following questions:

- *What influences the development of structural materials and forms?*
- *How do structural materials develop?*
- *What is material-adapted form?*
- *How can this knowledge be used to develop material-adapted forms?*

To achieve that objective I will:

- identify and define those influences, in addition to material properties, that affect structural form development.
- suggest how the knowledge from these analyses can be used toward the development of material-adapted forms for new materials.

The product of this thesis will be:

- a Form-Finding Influence Interaction Model that defines how the individual influences interact and their place in the form-finding process.
- a working definition of material-adapted form.
- an examination of the development of FRP to date; and a prediction of future development based on the analysis of material development made in this thesis.

1.3 Hypotheses

Material-adapted structural forms implicitly entail some direct correlation between a form and a material's structural properties. Indeed, this thesis began with the assumption that material properties dictate the development of structural materials. Based on early research, I hypothesized that *a material's structural properties do not unilaterally determine material-adapted structural form* because the process of form-finding is influenced by non-structural considerations too.

This thesis also examines the hypothesis that *materials are first used substitutionally before material-adapted forms are developed*, an observation that led to this project's conception.

1.4 Methodology

1.4.1 General Overview

This thesis is based on my research of the historical developments of structural materials. From this research, I analyzed how material-adapted forms evolved. The focus of this thesis is on the relationship between structural materials and structural forms used for building and bridge construction.

This project could have been approached from the following perspectives:

1. Make a catalog of structural forms from historical examples; and analyze these forms for material appropriateness as defined by a material's unique set of properties.
2. Study the general history of material development, including technological developments in material processing and construction methods. The scope of research includes historical context (vis-à-vis economy, socio-political factors, and general developments in technology), and, where possible, the thoughts and knowledge of the persons involved.

I rejected the first option as too restrictive. It relies on the current state of knowledge about materials science, structural theory and analytic methods. My rejection stemmed in part from an example given by Tom F. Peters, a historian of building technology, about early truss designs from the sixteenth and seventeenth centuries.[3] (**Appendix A-03, p.A.82, Fig. 5**) Peters demonstrated that trusses of that period cannot be analyzed using today's

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[3] Peters, p10.

understanding of trusses. Trusses were not conceived as singular systems, but rather as an overlay system comprised of simple king post and the queen post systems. (**Appendix A-03, p.A.83, Fig. 6**) The designers added standard structural units to achieve a desired span. This example emphasized the importance of understanding not only the relationship between materials properties, form and application, but also what the designers knew and thought.

I committed to the second approach because it would best answer the *why* and the *how* of structural development. Instead of examining structures solely with contemporary knowledge, I have tried to understand the context within which these structures were made. The need for this approach is evidenced by the example of a cast-iron beam published by English engineer Thomas Tredgold in 1822. The beam is an **I**-form with symmetrical flanges. The flanges and web all have the same thickness. (**Appendix A-03, p.A.100, Fig. 30(a)**) When I first saw this beam, I thought I had found the first instance of the standard **I**-section known today. Further analysis reveals that this symmetrical form is structurally inappropriate because cast iron is about six times stronger in compression than in tension. This is not a case of substitution because it is the first example I have found of the symmetrical **I**-section to that date. To explain this form, I had to discover that Tredgold performed erroneous tests. He determined the strength of cast iron based on the deflection of a test beam due only to its self-weight. Tredgold mistakenly assumed the material equally strong in compression and tension. To answer why the web is as thick as the flanges I had to further learn that Tredgold was addressing the practical problem of high internal stresses due to uneven cooling of a metal casting that can cause the metal to crack.[4] Knowledge of how we process *steel* today would not have been sufficient to explain Tredgold's design.

1.4.2 Research Activity

My research began with technological thought and knowledge.[5] At the time, I thought that I would be able to explain the process of form-finding by a thought-process model. I had to temper my ambition to focus on first identifying and analyzing the different influences on the development of structural form from the vast amount of historical information I referenced. This initial period of theoretical and philosophical research helped form my thoughts toward the subject of this thesis. Therefore, my analysis indirectly incorporates this research.

In the second phase of the project, I broadly researched the development of all structural materials over all time. The number of texts written on the history of structural developments in the nineteenth century is disproportionate to any other time in history. Technological history of the pre-Industrial era is especially deficient. Fortunately, the influence of technology is becoming more important in the fields of anthropology and archeology, which will greatly change our perception of history.[6] During this phase, I consulted many more references than the five hundred recorded in my database. Except for iron, I relied on two main sources for information: historical anthologies; and contemporary sources from the periods covered, such as journals and first-person accounts. **Chapter 02** provides an overview of the sources consulted.

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[4] Tredgold, p55-56.

[5] For references, see **Chapter 02**, State of the Art.

[6] Recent analysis of the Egyptian pyramids by Craig B. Smith, a professional construction project manager, and of the Inca ruins at Machu Pichu by Kenneth R. Wright, a hydraulic engineer, have shed new light on how those civilizations built cities and the extent of their technological knowledge.

I made several case studies in the final phase of my research. The purpose of these case studies was to research the influences on the development of structural form in more detail. The case studies were chosen to cover a wide range of history and represent significant periods of transition. A period of transition is either when a new material is first used in significant structural applications or when there is a major shift in material use from one material to anther. Most structural development has occurred since the seventeenth century. The principal structural types before then were the beam and arch. There are notable exceptions, such as the development of suspension bridges in China or South America, but these are of limited historical value. The most significant advances in structural form and theory between the seventeenth and twentieth centuries have primarily occurred in Europe, Russia and North America.[7] Contemporary design practice is based on this legacy.

The first case study is *The Beam and Arch in Greek Antiquity*. This case study addresses the transition from wood to stone as a building material in Greek civilization, as well as the question of whether stone was inefficiently used as a beam simply because it was directly substituted for wood. Finally, this case study explores why the Greeks rarely used stone to make arches, a far more efficient structural form that the Romans later exploited. The Greeks knew of the arch as early as the fourth century BC.

The second case study is *Telford's Menaï Suspension Bridge*. Thomas Telford, a Scottish engineer, was a pioneer of wrought-iron chain suspension bridge construction in the early nineteenth century. Britain was primarily using cast iron in construction at this time, but new smelting processes were making wrought iron less costly. Telford was a mason by trade and had principally designed arch structures in stone and cast iron. Therefore, we can study how Telford himself made the transition from thinking in terms of compressive structures to tensile structures.

The third case study is *Britannia Bridge, Why a Tube?* The Britannia Bridge, built over the Menaï Strait between England and Wales in 1850, is a canonical engineering structure. Robert Stephenson, the chief design engineer for the project, conceived of a radical new structural type, the tubular beam. This structural form was the result of particular site constraints and the limited number of structural systems available at the time. The wrought-iron tubular beam was the product of an intensive research and development effort conducted by William Fairbairn, an English industrialist and engineer, with Eaton Hodgkinson, an English engineering researcher and theoretician. The completion of the Britannia Bridge marked the end of most cast iron construction, and the emergence of wrought iron as the preeminent structural material.

The fourth case study is on the development of aluminum and plywood as structural materials in rigid airships from 1891 to 1940. The reason I have exceptionally chosen to examine a non-building or bridge structure is because both aluminum and plywood were practically new materials (for structural applications) when they were employed to build airships that ranged from 147 m to 245 m long. Aluminum and plywood are also notable for being materials created by man. Aluminum does not exist naturally in its metallic state. Man could only put this material to use because of developments in chemistry. Plywood is one of

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[7] This statement is based on the history of structural mechanics and theory recorded by Stephen P. Timoshenko in his book *History of Strength of Materials*.

the first engineered materials. It was made specifically to address the natural deficiencies of wood due to expansion and shrinkage. Furthermore, the airframes of these airships were important antecedents to the spatial structures developed for building construction. Airship technology contributed to the development of lightweight structures, processing technologies, structural theory and analytic methods, adhesively bonded and riveted structures, and folded and pressed thin-wall structural components.

The fifth case study is *The Flat Slabs of Turner & Maillart*. This study examines the general development of reinforced concrete and, in particular the development of reinforced concrete floor systems. The most successful reinforced concrete construction systems at the turn of the twentieth century supported the floor with a hierarchical system of girders and floor beams – an apparent substitutional form characteristic of steel or timber construction. C.A.P. Turner (USA) and Robert Maillart (Switzerland) independently developed the flat slab, a two-way spanning system that eliminated the floor beams and in the process created a new structural type. The flat slab is special because it broke the mold of two-dimensional structural conception synonymous with timber, iron, and steel construction.

The last case study is *Prestressed Concrete Bridges*. Prestressed concrete, like plywood, is the product of material deficiency, specifically concrete's tendency to shrink, creep, and crack. Engineers Eugène Freyssinet (France) and Franz Dischinger (Germany) independently studied the problem of shrinkage and creep. Both men were able to derive analytic methods to predict the shrinkage and creep behavior of concrete. They began developing prestressing from this new knowledge. This case study traces the historical development of prestressing and its use in bridge construction. Prestressing made it possible to build far longer spans with concrete than engineers had accomplished before. As these spans grew, construction methods were adapted to overcome the problem of formwork needed for constructing concrete structures. This study reviews the development of these structural methods and the eventual development of external prestressing.

Collectively, these case studies constitute the data of this thesis.

1.4.3 Choice of Engineering Materials Researched

Engineering materials are generally classified as *metals*, *polymers*, *elastomers*, *glasses*, and *ceramics*. Combining two or more different materials to create a third material with distinctly different properties than those of the constituent parts constitutes a *composite*. Materials from all of these 'families' are used for structural applications in construction.

The case studies broadly cover the most widely used materials in construction, particularly those relevant in the past two hundred years. They are: stone, cast iron, wrought iron, aluminum, plywood, reinforced concrete and prestressed concrete. I have not studied the development of wood in detail to limit the scope of the research and because I do study plywood, a derivative material. I have not included steel because little development has occurred in relation to component form since the nineteenth century developments of wrought iron.[8] The primary advances have been made in making stronger alloys and advanced analytic methods that make it possible to build structures larger, longer and higher.

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[8] The recent development of steel foam materials holds the potential to exploit the structural potential of steel by making it possible to fabricate stiff, lightweight plates, or even more complex, three-dimensional forms.

I use FRP as a test case study because of its particular stage of development today. FRP, a product of the 1930s, was experimented with in the late 1950s, 60s and early 70s, but failed to gain wide market acceptance. FRP use in construction began to rise in the last ten years after a lull of nearly two decades. The pultrusion process makes prismatic structural forms affordable enough for wider application within the industry. This is a material in a period of transition. **Chapter 06** examines the future development of FRP in more detail.

It would have been too limiting to pick one material to study because the general characteristics of material development would have been difficult to discern without comparison to other materials. Furthermore, it would be impossible to conclude that particular characteristics of a past development, say in the nineteenth century, would be applicable today because of the widely different socio-economic context and levels of knowledge existing in the two periods.

1.4.4 Analysis

This thesis can be analyzed from two distinct perspectives:

1. The *Designer*: who is a person or group involved in design activity whereby material choice is an important factor in the form-finding process. The freedom of choosing structural form is greatest if the designer can tailor material choices to the most efficient structural model defined by statics.

2. The *Developer*: who is a person or group committed to improving the state of the art of a specific material (i.e. material choice is pre-selected). Freedom of structural form is necessarily limited and the Developer must vet forms using some type of material suitability criteria.

This thesis is primarily written for the developer who is seeking to advance the state-of-the-art of a particular material. If the processes of material development and form-finding can be determined, then the potential exists to accelerate market acceptance and the number of applications of a material. However, I do not know how to measure this.

The designer is addressed where issues of material choice arise. The aspects of this thesis about form-finding are equally applicable to the designer and the developer.

My limited professional experience is a disadvantage to my analytical thinking. I have had to rely on “book” knowledge to best fill in the gaps. To this end, I have learned and formulated my ideas about the design process and problem solving vicariously through the biographies of Thomas Telford, William Fairbairn, Ferdinand von Zeppelin, and scientist Richard Feynman, in addition to the numerate examples recorded in several books on technological thought.[9] My initial research of texts on technological thought and knowledge has further influenced my thinking.

Since it would be impossible to reference, or even trace, every historical fact that has influenced my analysis and conclusions, I use specific examples in the text to support specific points. The annexed case studies support these points more broadly.

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[9] Ferguson (James Naysmyth and the steam hammer); Reynolds (William Sellers and the standardization of screw threads); Peters (Guillaume-Henri Dufour and wire-cable suspension bridges).

1.5 Organization of the Thesis

Ch.02: State of the Art

This chapter presents a selected review of sources related to the subject of this thesis. An indexed, general reference bibliography is provided at the end of the chapter. The bibliographic information of footnoted references is found at the end of each chapter.

Ch.03: Structural Form

This chapter defines different aspects of form. A hierarchy of structural form is presented that categorizes structural form as: *Structural Systems and Global Form, Structural Components and Local Form, Structural Elements and Material Architecture,* and *Structural Details and Detail Form*.

Structural Systems are further classified by a structural typology. The typology used in this thesis comes directly from Heino Engel's book, *Structural Systems*.

Structural form is also distinguished as being one of three types: *Ideal Form, Constructible Form,* and *Implemented Form*.

Ch.04: Influences on the Development of Structural Materials and Form

This chapter examines the influences on the development of Structural Materials and Form. I have identified the following Influence Categories from my research: *Function, Material Properties, Processing Technologies, Connection Technology, Construction Process, Economics, Socio-Political Factors, Knowledge,* and *Technological Thought*.

A Form-Finding Interaction Model is presented at the end of this chapter. This model shows how the various influences are inter-related and affect the form-finding process. The usefulness of Engel's typology of structures and Michael F. Ashby's material selection charts is discussed.

Ch.05: Material-Adapted Form

This chapter derives the definition of material-adapted form. It examines what the *nature* of a material is and what qualities constitute *good* structural form. A working definition of material-adapted form is presented. The hypothesis of material substitution is addressed in the context of what material-adapted form means and the general history of materials.

Ch.06: FRP Test

This chapter tests the applicability of the analysis presented in this thesis to the development of FRP. This chapter will: briefly review the historical development of FRP materials; compare that history with the Material Evolutionary Groups; evaluate past and current applications against my definition of material-adapted form, project possible future developments; and present recommendations for furthering the development of FRP today.

Ch.07: Conclusions

The conclusions contain a summary of my findings and present general proposals for developing structural materials and material-adapted forms. Suggestions for further research are included.

Appendices A-01 to A-06: The Case Studies

These appendices comprise the aforementioned case studies. They are the data of this thesis.

Appendices A-07 to A-08: Form-Finding and Material Selection Aids

These two appendices contain reference material copied from Heino Engel's *Structure Systems*, and Michael F. Ashby's *Materials Selection in Mechanical Design*. This material is used for reference purposes only and will not be reprinted for publication.

Appendix A-09: Chronologies of Material Evolution

Several detailed chronologies of material development are presented to complement **Appendix A-10**, *Material Evolutionary Groups*. These chronologies loosely show the relationship between the influences of processing technologies, economics, and the development of material-adapted forms and applications.

Appendix A-10: Material Evolutionary Groups

The general evolution of structural materials is relevant to answering why structural forms have developed as they have. However, this study was outside the immediate scope of the thesis. This appendix begins to evaluate the characteristics of material development by examining the more broad evolution of materials, rather than focus on particular developments. This knowledge is used to analyze the development of FRP in **Chapter 06**.

1.6 Vocabulary

1.6.1 Hierarchy of Structural Form and Form Types

This thesis incorporates several classification systems of structural form. **Chapter 03** describes these classification systems in detail. To summarize, two hierarchies of structural form are introduced that distinguish between structural systems, which may be comprised of several structural parts, and the parts themselves. The vocabulary of these hierarchies is strictly technical. It physically describes specific structural parts. I also introduce an original classification system to distinguish form *types* that are conceptual in nature. This system forms the basis of a form-finding model presented at the end of **Chapter 04**.

The first hierarchy describes structural form as being *Global Form* or *Local Form*. This hierarchy is used in other references, such as Bjørn Normann Sandaker's dissertation *Relfections on Span and Space* (2000).

Global Form refers to a complete structure, such as a bridge or building. The structure may be described as being an arch or a moment frame. Global Form can be more specific by breaking down a bridge structure to be comprised of arch, spandrel, and deck structures. Each of these structural parts can be viewed as independent, global entities, depending on the structural model, whereas, the piers of a frame-type bridge cannot be separated from the deck structure because the deck and piers comprise a unique, structural whole.

Local Form is a combination of geometric form derived from mechanics influenced by a material's structural properties, and processing and constructive attributes.

The classification system of Global and Local Form is used sparingly in this thesis. Local Form is not precise enough to account for the complexity inherent in the conceptual design of the bar-angle in comparison with that of the bolted connection. It is my opinion that the limits of this classification system hindered Sandaker's analysis. **Section 2.5** reviews his work in comparison to this thesis.

I have created a more detailed hierarchy: *System Form*, *Component Form*, *Element Form*, and *Detail Form*.

System Form is the equivalent of Global Form, however I have incorporated the work of architect Heino Engel, published in his book *Structure Systems*, for further precision. See **Chapter 03** and **Appendix A-07** for more detail.

Component Form refers to the form of the bar-angle, or any other sub-part that is *visible* with the exception of *details*.

Detail Form refers to connections, stiffeners, or any other like parts of a structure. This denotation is consistent with conventional practice, as evidenced by conventions of construction drawing, typical of all materials, and the field of steel detailing.

Element Form is specifically addresses the particular characteristics of composite materials vis-à-vis the arrangement of the constituent parts, such as the placement of rebar in reinforced concrete or the type of fiber textiles used in fiber reinforced polymer composites.

Material Architecture is a term that is related to, but more generic than, Element Form. Material architecture describes the microstructure of homogenous materials such as metals. Material architecture can refer to Element Form or the microstructure of the fibers or composition of the matrix materials, such as the material used in a concrete mix design.

The conceptual form types I have created are: *Ideal*$_1$ *Form*, *Ideal*$_2$ *Form*, *Constructible Form*, and *Implemented Form*. These terms relate to systematic stages of design development described in the Form Finding Model at the end of **Chapter 04**.

Ideal$_1$ ***Form*** is defined to be the System model that most efficiently satisfies the structural requirements while meeting all the functional requirements of the project. This model is constructed from statics and structural system models that are not material specific. The model is described by a wire-frame and surface diagram.

Ideal$_2$ ***Form*** is generated by introducing material specific properties such that the form of the system Components is defined. This stage of design can result in either a *Structural Ideal*, which results in a minimal material structure, or an *Integrated Ideal*, that considers issues of function integration. Function integration is described below and in **Section 4.2.6**. Ideal Form is generated without regard for cost or technological limits of fabrication or construction. Element Form can also be developed as part of the Ideal$_2$ Form.

Constructible Form is a structural form based on the Ideal model that can be fabricated and constructed using existing technologies without regard for cost. Detail Form is created during this stage of design development.

Implemented Form is the structural form that is ultimately constructed. Economic issues are generally the most significant parameter determining which forms are implemented.

1.6.2 Evolution vs. Development

I use the terms *evolution* and *development* in this thesis. The use of the word *evolution* in reference to technology is a particularly contentious issue to some in the field of technological history.[10] In this thesis, ***evolution*** is not used in the context of implying that the theories of natural evolution can be applied as a model for defining or explaining technological change. Rather, I use *evolution* to describe a general state of progress made with respect to changing applications and forms over the course of a specific material's use. A ***development*** describes a clearly inter-linked effort to actively grow and promote the use of a material. The invention of the flat slab, an improvement upon the conventional beam-slab system, was a *development*. The historical record of reinforced concrete's transition from Joseph Monier's flowerpots to the thin shells of Eduardo Torroja can be broadly referred to as an *evolution*. That is, the *evolution* of a structural material is characterized by numerous *developments*.

1.6.3 Construction

This thesis is primarily concerned with the development of structural forms for bridge and building construction. The term ***construction*** refers to these types of structures unless otherwise noted.

1.6.4 Civil Engineering Structures and Persons

Unless otherwise noted, terms such as: ***engineering***, ***structure***, ***designer***, ***developer***, ***engineer***, or any variants thereof refer to the field of civil engineering that is devoted to the design of buildings, bridges and other structures that make up infrastructure. I will make every effort to avoid confusion when writing about persons or structural types from other engineering disciplines such as aeronautics or mechanical engineering.

1.6.5 Designer vs. Developer

See also **Section 1.4.4**

Designer: a person or group involved in design activity whereby the principal objective is to produce a product and material choice is an important factor in the form-finding process.

Developer: a person or group committed to improving the state of the art of a specific material.

1.6.6 Aspects of Function

See **Section 4.2** for more complete explanations of the following terms:

Function: this term is used broadly in this thesis to include both structural and non-structural purposes of structure. That is, function includes not only a load that a structure must receive and transfer, but also its purpose as it relates to the program of a constructed project. The structure may have to be flat to be used as a floor in an office, or it may have to take an unusual shape to conform to architectural issues of aesthetics and expressive form.

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[10] Basalla; Dreicer.

Function Pattern: a tool I have created to create graphical models that define the space within and without which a structure can occupy. Load conditions that will not change regardless of the structural system or form can be added to this model, which I similarly call the Load Pattern.

Function Integration: a term that refers to the process of designing a structure to serve a purpose secondary to its primary load bearing function. Function integration can be either *integral* or *complementary*. Integral integration is when a structure performs a second function directly, such as the reinforced concrete deck of box-girder bridge that serves as a compressing member of the structural beam as well as the flat surface over which traffic will travel. Complimentary integration is when a structure is designed to accommodate a separate function made of different building components, such as HVAC[11] systems.

1.6.7 Composite Materials vs. Composite Structures

Composite Materials: Materials made from two or more distinct materials, whereby one or more of the materials complements another material's deficiency.

Composite Structures: Structure made of components fabricated from two or more distinct materials, such as a composite steel-concrete bridge composed of steel plate girders and a reinforced concrete deck.

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[11] HVAC = Heating, Ventilation and Air-Conditioning; includes water pipes and air conduits or ducts.

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STATE OF THE ART

02

2.1 Fields of Research Related to this Thesis

The principal axes of research for this thesis can be divided into the following three categories of inquiry:

- *Design, Knowledge, and Technological Thought*
- *The General History of Structural Materials and Forms*
- *Philosophy of Form and Structural Form*

The following sections review the relevance of these categories to this thesis and the types of sources referenced. The chapter concludes with an examination of two sources whose subject matter is similar in certain respects to this thesis. I will explain why this thesis is different from and adds to the state of the art.

A bibliography, indexed under the titles of the above listed research categories, is provided at the end of this chapter. This bibliography is not comprehensive; it is intended to list some of the more important references I have found and is representative of the types of sources available.

2.2 Design, Knowledge, and Technological Thought

2.2.1 Introduction

The first phase of my research concentrated on the subjects of design, knowledge, and technological thought. My interest in design centered on philosophies of design and design as a process. I researched two aspects of knowledge. The first pertains to what structural designers knew and when, particularly with respect to structural theory and material science. The second aspect is concerned with how knowledge is created and disseminated. The last subject, technological thought, is an important field whose purpose is to comprehend the processes of thinking and ideation that lead to the creation of technological artifacts. This initial research influenced my thoughts when developing the design model presented at the end of **Chapter 04**. As discussed in the Introduction, I did not integrate this information as completely into my analysis as intended. This section gives a solid overview of the applicable references in this subject area. These references can be used as a basis for further research in order to integrate technological thought more substantially into the substance of this thesis.

2.2.2 The Philosophy and Process of Design

The nature and philosophy of design has been written about both generally and specific to certain disciplines. These sources variously address the design process comprehensively or focus on specific phases of the process.

In 1991, William Addis wrote an article about structural engineering design published in *Transactions of the Newcomen Society* entitled "The Evolution of Structural Engineering Design Procedures: A History of that Skill Called Design." Addis approaches engineering design philosophically. He is clearly in the early stages of his research and thoughts on the topic. Addis primarily poses questions and hypotheses about the nature of the structural engineering design process that require further examination. He observes that the history of engineering seldom goes beyond the fact that such figures such as Brunelleschi or Brunel designed famous buildings or bridges. That is, there is a lack of insight into why and how these persons accomplished what they did. Addis further asks why engineering design has not attracted more interest from philosophers and historians.[1] Actually, the field of technological thought began to be formed in the 1950s, with the publication of the quarterly journal *Technology and Culture* (1959 – present). However, Addis' criticism that little overall research had been done is valid. In response to Addis's article, Rowland J. Mainstone, a historian of building technology, noted that designing was a very different activity from seeking a scientific explanation for a particular category or experience. Mainstone saw "the essence of structural design as being the very human activity of making particular kinds of choice."[2] I will address Mainstone's work and thoughts on the subject of design and the development of structural form in more detail below. In 1999, Addis edited a book entitled *Structural and Civil Engineering Design*. This book is one effort to rectify the dearth of attention Addis perceived to have been given to the subject of design philosophy and process in 1991.

J.E. Gordon presents a philosophy of design at the end of his book entitled *Structures, or why things don't fall down* (1978). Gordon bases his philosophy on the work of H.L. Cox, who was an exponent of the mathematical study of the philosophy of structures in the 1970s. Gordon argues that structural design should be governed by shape, weight, and cost. He discusses the relative efficiencies of tensile and compressive structures, pointing out that the weight and efficiency of tensile members is a function of length and size because of the necessity for heavy end fittings. He also reviews the merits of: monocoque versus space frames, pneumatic structures, and other structures. The crux of his argument is structures should be evaluated on the basis of energy costs.

Engineering Design, first written by Gerhard Pahl and Wolfgang Beitz in 1977, is a classic treatise on the design process. The author's present a comprehensive, systematic approach to design. Their purpose is to provide an organizational framework for design to meet the needs of modern engineering design, which often involves managing the work and communications of a large team. Though this book focuses on industrial product design, it is useful to structural engineering as well. Louis Bucciarelli studied the practical implementation of team-oriented design in his 1994 book *Designing Engineers*. Bucciarelli observed the design development of several industrial products, giving valuable insight into

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[1] Addis^2, p55.
[2] Addis^2, p63.

the dynamics of design done within the organization framework of corporations. Bucciarelli's observations of group dynamics and analysis of how certain design management methodologies worked is of value to structural engineering since the largest engineering firms today are run as corporations and do not resemble the small engineering office of yesteryear. I was unable to integrate the dynamics of corporate and team design into this thesis. It is certainly a subject that needs to be examined in more detail.

Kevin Potter presents a simplified, but comprehensive, design-model in his book *An Introduction to Composite Products: Design, Development and Manufacture* (1997). Potter's perspective is centered on the design of fiber reinforced plastic composite products. Potter's model is characterized by design cycles, or feedback loops, whereby each phase of design requires certain requirements be met before design can proceed to the next phase. Potter's model had some influence on the process modeled at the end of **Chapter 04**, though the two models are distinctly different because Potter's model is based on his experience and is focused on product development. I derived my model from historical examples and focused on the relationship between form-finding and the development of material-adapted forms.

Michael F. Ashby's *Materials Selection in Mechanical Design* presents a detailed model for one particular part of the design process, material choice. Ashby has created charts that compare different combinations of material properties and attributes from which materials can be selected that best meet the designer's specified criteria. I have annexed copies of some of these charts in **Appendix A-08**. Ashby's method seems like an extremely powerful tool in design that is perhaps under-exploited. I have not found a source that evaluates the practical application of his method. I present Ashby's method as a possible tool in the design process because it can free engineers from the material constraints of their own limited experience with materials. Ashby's book uses a broad array of examples that include structural engineering applications. He emphasizes the interaction between function, shape, material, and processing.

2.2.3 Knowledge of Mechanics of Materials and Materials Science.

The historical development of structural theory and mechanics of materials is well covered in three sources: I. Todhunter and K. Pearson's *A history of the theory of elasticity and of the strength of materials from Galilei to Lord Kelvin* (1893); Stephen P. Timoshenko's *History of Strength of Materials* (1953), and Jacques Heyman's *Structural Analysis, a Historical Approach* (1998). Timoshenko's book is a particularly good source. However, his perspective is somewhat biased towards an iron and steel centric view and does not satisfactorily address other major engineering materials. Heyman's book is a useful source of information, though it is more limited in scope than Timoshenko's. It does not satisfactorily fill in the gap between 1953, when Timoshenko wrote his book, and today.

There are surprisingly few sources about the development of materials science and its role in the development of materials. The best source I have found is J.E. Gordon's *The New Science of Strong Materials* (1976). Gordon traces the advances made in the knowledge of materials science from World War II to the 1970s. He shows how this knowledge was used to develop materials such as plywood and fiber reinforced composites. Gordon also demonstrates the value of understanding materials science to explain the macro behavior of conventional materials such as steel and natural wood.

2.2.4 Creation of Knowledge and its use in Design

Walter G. Vincenti has written two books about the creation of knowledge and its use in design. In 1978, Vincenti and Nathan Rosenberg wrote about the generation of knowledge and it use in developing the tubular forms of the Britannia Bridge. The book's title is *The Britannia Bridge: The Generation and Diffusion of Technological Knowledge*. In 1990, Vincenti wrote *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History.* Both of these books examine how knowledge is created. In the book on Britannia Bridge, the authors show how the knowledge generated from the development of one structure was used in interdisciplinary applications such as ship and crane construction. The focus of Vincenti's second book is on the creation of knowledge by a process of parameter variation. He also examines methods for defining design requirements and generating data for design. At the end of the book, he defines an "anatomy of engineering design knowledge" and proposes a model for generating engineering knowledge.

Henry Petroski presents his theory about the role of failure in design in several books. Petroski posits that failure and technological progress are inseparable. He uses a wide range of examples to demonstrate the causal effect of failure on design; from bridges to forks to aluminum can pop-tops. It is fun reading and an important influence to consider in any model of technological development. Petroski's books lack a clear explanation of how lessons are learned from failure and how that knowledge translates into technological thought.

Other sources could be named here, but are better included below under the category of technological thought. The subjects of knowledge and technological thought are intrinsically linked and difficult to separate. The division here is somewhat arbitrary and based on whether one subject is emphasized more than the other in a given source.

2.2.5 First Person Accounts

First person accounts of the design process are the best sources from which we can gain insight into the processes of ideation, creation and design. Through the centuries, designers have generally left relatively little record of their thoughts during design. Most records are accounts of the finished product and cleansed accounts of how those solutions were arrived at. I use the word 'cleansed' because accounts written after the fact will be influenced by hindsight and important decisions based on false assumptions or mistakes could be filtered out. I have found a number of good first hand accounts, thought their value varies from one source to another. When choosing my case studies I tried to look for examples where I could access first hand accounts. This was not possible for the Greek case study.

For the case study on the Menaï Suspension Bridge, Thomas Telford's chief engineer, William A. Provis, wrote an account of its design and construction in a book entitled *An Historical and Descriptive Account of the Menaï Suspension Bridge* (1828). Furthermore, I could gain insight into Telford's approach to the design from his autobiography and an article he and Alexander Nimmo wrote about bridge design in 1811 for the *Edinburgh Encyclopedia*. The autobiography is particularly useful to understanding his background and appreciating how he made the transition from stonemason to the 'father' of civil engineering.

Historians of building technology have written extensively on the Britannia Bridge because by the primary persons involved in its design documented its development exceptionally well. Edwin Clark and William Fairbairn both wrote books describing the development and construction of the Conway and Britannia tubular bridges. Clark presents Robert Stephenson perspective. Fairbairn was the industrialist/technologist who oversaw the experimental development of the tubular section. Fairbairn's book includes letters and reports written by himself, Robert Stephenson, and Eaton Hodgkinson. Hodgkinson, a material scientist, was responsible for establishing a theoretical explanation for the buckling behavior of the tubular section. These accounts were written because of disagreements among themselves about the level of credit each person deserved for the development of this innovative structural form.

For the airship case study, I have many documents written by Ferdinand von Zeppelin himself. These documents are especially useful in understanding the conceptual development of his idea from its earliest stage to the construction of the first airship in 1900. Unfortunately, Zeppelin's most important papers are in his diary, which his family has kept sealed from researchers since the 1930s. Hugh Eckener, a close friend and employee of Zeppelin's, is the only non-family member who has had unrestricted access to Zeppelin's diaries. Eckener's (sympathetic) biography of the Zeppelin gives the best insight we have into the contents of Zeppelin's diary. Ludwig Dürr, chief design engineer for Luftschiffbau Zeppelin from 1900 to 1940, wrote a thorough summary of the development of Zeppelin airships in 1924. Johann Schütte, co-owner and design engineer for Luftschiffbau Schütte-Lanz, edited a comprehensive review of the development of the Schütte-Lanz airships in 1926. These are the best overall reviews of these developments. There are thousands of individual documents in the Zeppelin archives, though a lot of information was lost during the two world wars.

There was limited firsthand information available for the flat slab case study. I had to primarily rely on articles written by C.A.P Turner and Robert Maillart to have some insight into their thoughts when inventing the flat slab. David Billington has written extensively on Robert Maillart, and his 1997 biography of Maillart, *Robert Maillart: Builder, Designer, and Artist*, draws heavily from Maillart's personal documents, providing the best insight into his life and thinking that I have referenced.

Eugène Freyssinet wrote several papers and books on the subject of prestressing. Each gives some account of his thinking as he identified and addressed the many unknowns and problems associated with prestressed concrete.

Other engineers for whom there are first hand accounts that could be studied are: Alexandre-Gustave Eiffel, Eladio Dieste, Eduardo Torroja, Ove Arup, and Peter Rice.

2.2.6 Technological Thought

Technological thought is an important subject related to the development of structural materials and forms. The subject of technological thought has grown in importance in parallel with the increasing attention paid to the history of technology. This area of inquiry is important to historians, archaeologists, and anthropologists so that they can better understand human civilization and history. This subject is also pertinent today because of its indispensable application to the development of artificial intelligence.

While various journals and biographers have recorded the history of building technology since the eighteenth century (see History of Building Technology below), the study of technological thought is a recent field of inquiry. It was arguably begun at the end of 1950s by the publication of the quarterly journal *Technology and Culture*. The *Transactions of the Newcomen Society* (1922-present, UK) and the *Technikgeschichte* (1933-present, Germany) are also important to the development of this field. Leaders in the field include Edwin T. Layton, Jr., Terry S. Reynolds, George Basalla, Eugene Ferguson, and Subrata Dasgupta. Authors who specifically examine the relationship between building technology and technological thought are: Antoine Picon, Ulrich Pfammatter, and Tom F. Peters.

Layton and Reynolds have both written about the development of technology in America, examining the cultural and contextual influences on technological change that were distinctive from other parts of the world, particularly Europe.

Basalla analyzes the merits of the evolutionary model applied to technological development in his book *The Evolution of Technology* (1988). His book includes interesting chapters about the influences of socio-political factors and economics on the development of technology. Basalla notes that the histories of the social or psychological sciences provide inadequate explanations for the appearance of novel artifacts within the made world. Basalla explores a number of the major sources of novelty without formulating a comprehensive theory to explain its emergence. The foundation of his evolutionary model is the concept that diversity stands at the beginning of evolutionary thinking.[3] I do not agree with all of Basalla’s arguments, but I do agree that there is a relationship between diversity and technological progress.

Eugene Ferguson writes about the importance of visual thinking in *Engineering and the Mind’s Eye* (1993). Ferguson emphasizes the need to maintain systems of engineering education that encourages non-verbal thought to ensure engineers do not become reliant on mathematical models that do not necessarily reflect the behavior of technological artifacts in the real world.

In *Technology and Creativity* (1996), Subrata Dasgupta begins to quantify how we think. He presents the idea of knowledge *tokens* that are enabling parameters of creativity, and he proposes a descriptive thought process model based on *if – then* statements. This type of analysis is amenable to his interest in applying an understanding of technological thought to the development of artificial intelligence. Dasgupta uses the development of the Britannia Bridge as a case study to show the relationship between knowledge, ideation and creativity.

Collectively, the books of Antoine Picon, Ulrich Pfammatter and John Hubbel Weiss present a comprehensive analysis of the development of the distinct fields of architecture and engineering in the eighteenth and nineteenth centuries. In *French Architects and Engineers in the Age of Enlightenment* (1992), Picon records the transformation of architects clinging to a classical, beaux arts system of design and having to adjust to the functional imperative of the Industrial Revolution and iron, the new building material. Picon describes how the

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[3] Basalla, p208-209.

engineer emerges as the leader of human progress in the nineteenth century. Pfammatter's book, *The Making of the Modern Architect and Engineer* (2000), traces the development of architecture and engineering education. Pfammatter emphasizes the importance of the French *écoles* and their influence on pedagogic models of teaching that led to the modern polytechnic education system. Pfammatter illustrates the importance of *how* people learn, as much as *what* they learn, to influencing the way in which people think. In *The Making of Technological Man…* (1982), Weiss examines the socio-political influence on the development of French technical education.

Since the late 1970s, Tom F. Peters has been developing a refined theory of the role construction process has in the progress of building technology. In his various writings, Peters has put forward a model of technological thought based on what he calls *matrix thinking*, which emphasizes lateral, rather than vertical, thinking. The distinction here is in the details, whereby the ‘detail' in structural design, is as important hierarchically as the overall system. The most complete examination of his theories is in his book, *Building the Nineteenth Century* (1996), but I have found that his article in *Perspecta 31*, “Technological Thought is Design's Operative Method” (2000), the best explanation because of its conciseness.

2.3 General History of Structural Materials and Forms

2.3.1 Introduction

The second phase of my research was a broad based review of the history of building technology, structural materials, and the development of particular structural types such as the truss or the I-beam. I used historically contemporaneous sources where possible, but much of my research relies on the historical accounts of others for no other reason than the shear volume of information I was trying to access. It was imperative that this thesis examines a wide range of knowledge and examples. A review of more limited scope would have made it more difficult to distinguish between general trends of material development, and contextual trends that include short-term socio-political and economic conditions.

2.3.2 History of Building Technology

The history of building technology is itself a rather young field of research, having only really started in the 1960s and 70s. Important figures in this field specializing in building technology are: David Billington (USA); John G. James (UK); Rowland J. Mainstone (UK); Rowland Paxton (UK); Tom F. Peters (Switzerland/USA); Henry Petroski (USA); Ted Ruddock (UK); A.W. Skempton (UK); and ecyclopedists Bertrand Gille (France) and Joseph Needham (UK).

The history of the history of building technology can be traced to biographers Samuel Smiles (1812-1904, UK), Henry Howe (1816-1893, USA) and Conrad Mattschoss (early twentieth century, Germany). The history of building technology has principally been preserved in various journals and magazines. Some of the most important of these sources are: *Technikgeschichte* (1933-present, Germany); *Die Bauzeitung* (1953-1959, Germany), now *Deutsche Bauzeitung* (1960-present, Germany); *Schweizerische Bauzeitung*, now SIA

(1883-present, Switzerland); *Scientific American* (1845-present, USA); *Transactions of the Newcomen Society* (1922-present, UK); *Technology and Culture* (1959-present, USA); the *Annales des ponts et chaussées* (1831-present, France); *Revue générale de l'architecture et des travaux publics* (1840-present, France); and the *Allgemeine Bauzeitung* (1836-1918, Austria).

2.3.3 History of Structural Materials

Most histories of structural materials do not interpret why or how developments of material usage occurred. In most cases, these histories are simply efforts to preserve knowledge. David Yeomans gives a broad overview of material development to 1900 in his book *Construction Materials to 1900* (1997). Peters includes a brief review of the development of various engineering materials in his book *Building the Nineteenth Century*.

For iron, the most thorough accounting of its history and development is contained in Stephen J. Goodale and Ramsey Spear's *Chronology of Iron & Steel* (1931), which traces the history of iron from antiquity to the early twentieth century. Somebody ought to bring this book up to date to include developments from the 1930s, where the book leaves off, to today. S.B. Hamilton and R.J.M. Sutherland have written numerous articles about the development iron in the eighteenth and nineteenth centuries, primarily published in *Transactions of the Newcomen Society*. The Anglo-centric view of their work is somewhat counter-balanced by Frances H. Steiner's *French Iron Architecture* (1984), which provides valuable information about the early development of wrought iron in France while England was driving the Industrial Revolution forward with its cheaper cast iron. German author Peter Tunner wrote several important contemporary accounts of the development of the iron industry in the nineteenth century, however I was unable to find accessible copies. The Eisenbibliothek, located in Klostergut Paradies, Switzerland, is an archive dedicated to the preservation of the history of iron. It contains many valuable references, including most of those mentioned above.

The most complete history of concrete, reinforced concrete, and prestressed concrete is in the three-volume *Vom Caementum zum Spannbeton* (1964). Frank Newby edited a volume on the early development of concrete; however, it is not as good as the first cited source. Jean Louis Bosc's book *Joseph Monier et la naissance du ciment armé* (2001) gives a good history of the early development of reinforced concrete. Monier licensed one of the first commercially successful proprietary systems. Monier's German licensee Wayss & Freytag made significant developments in the technology of reinforced concrete. Other sources include works by Peter Cook and, for a good overview of the many proprietary floor systems patented in the late 19th century, see the book by Marsh & Dunn. Emil Mörsch and Fritz von Emperger wrote early texts on concrete design that give insight into the development of concrete design theory and procedures.

Historians have relatively ignored the histories of aluminum, plywood, and fiber-reinforced plastics. Most information I have found has come from contemporary sources about the state of the art of those materials, which often include short histories of the materials they are covering. More information would be available to me from industry journals, but I was unable to research these sources in detail. Most of my information about aluminum has come from Joseph W. Richards' second edition of *Aluminium: Its History, Occurrence, Properties*, published in 1896. General histories published by Hans Joliet and Sarah Nichols have also been useful. Nichols' book, published in 2000, helps to fill in the historical gap that exists between the 1950s and today.

For the history of plywood, I have had to rely almost exclusively on state of the art books that include historical summaries of the material's development. Peter's includes a short section on plywood and glue-laminated wood products in *Building the Nineteenth Century*, however I found the most complete histories in books by Andrew Dick Wood and Thomas D. Perry. F.F. Wangaard's book on wood and wood products provided further information. Terry Sellers' book *Plywood and Adhesive Technology* (1985) provides important information about the development of adhesives. The structural properties of plywood and its early development in structural applications is covered in both of J.E. Gordon's books, *The New Science of Strong Materials* (1976) and *Structures* (1978), however no source even mentions the use of plywood in the Schütte-Lanz airships, which predates the use of plywood in airplane construction.

A book dedicated to the history of fiber-reinforced polymers or structural plastics in general does not exist. What histories have been written are published in relatively short journal articles or, again, as a chapter in state-of-the-art books about the application and design of FRP structures. The best overall history of plastics I have found is in Arthur Quarmby's *The Plastics Architect* (1974). J.E. Gordon records the earliest developments of glass fibers and fibers made of other materials in *The New Science of Strong Materials*. Gordon was an important individual in those actual developments. Kevin Potter includes a short history of FRP at the beginning of his book *An Introduction to Composite Products* (1997), but the best history of FRP is in John Murphy's *The Reinforced Plastics Handbook* (1998). The most important information contained in this short, five-page summary, are the dates when significant processing technologies were introduced. Unfortunately, the authors of most of these summarized histories have not adequately referenced their sources, making it difficult to trace where the information has come from. Jeffrey L. Meikle wrote a full-length book about the cultural influences on the development of plastics, and the influence of plastics on culture in America. His book, *American Plastic* (1995), is a thorough analysis of the development of plastics in America, however his focus is on the use of plastic in ordinary consumer products and less on advanced applications in the building or aeronautic industries. *American Plastic* presents an interesting question about why Americans have accepted plastic in so many artifacts of everyday life, such as furniture, dishes, appliances and other products found in the home, but have not widely accepted houses built of plastic.

There is a dearth of information about the use of FRP in construction from the mid-1970s to the beginning of the 1990s. In the early 1990s, several publications examined the role of FRP in construction, such as *Plastics Composites for 21st Century Construction*, published by ASCE in 1993. Contemporary versions of this book, such as another book published by ASCE in 2001, entitled *Composites in Construction: A Reality*, only serve to show how little progress has actually been made to increase the use of FRP in construction since the early 1990s. Two magazines, *Reinforced Plastics* and *Composites*, record current developments and are among the best sources of information about the use of FRP in construction today. In 2001, Thomas Keller wrote a state of the art report on the specific use of FRP in bridge construction that is the best such compilation to date. With approximately 200,000 structurally deficient bridges in the United States alone, there is a large potential market for FRP that could prove critical to its wider acceptance and application in construction.

2.3.4 General History of Structural Forms

The general history of particular structural types such as the development of the I-beam, truss, or long-span roof, are principally to be found in articles published in the *Transactions of the Newcomen Society*, written by L.N. Edwards, J.G. James, Robert A. Jewett, R.J.M. Sutherland, and S.B. Hamilton. Ted Ruddock records the development of arch bridges from 1735-1845 in his book *Arch Bridges and Their Builders*, showing how the development of arch theory, particularly in France, affected the design and form of arch bridges. K.A. Faulkes gives a concise history of flat slab design procedures. This book, which records C.A.P. Turner's invention of the flat slab, traces the development of how the flat slab was (mis)understood as a structural type and how structural theories were developed to explain its structural behavior. Rowland J. Mainstone's *Developments in Structural Form*, traces the developments of the major structural base forms, such as the arch, domes, walls and slabs, beams, and tension structures. I will address Mainstone's work in more detail below.

2.4 Philosophy of Form and Structural Form

2.4.1 Introduction

Form is an inherently philosophical topic. Even if we consider apparently material or quantitative conditions governing the creation of form, such as the relationship between material properties and structural form, the thought processes used to generate form can constitute a philosophy of design by default. One purpose of this thesis is to define what *material-adapted form* means. In answering this question, I have broadly studied different aspects of form as it pertains to different philosophies about the so-called *nature* of form. This search has led me to review works on: the general philosophy of form; the relationship between natural or biological form and man-made form; the relationship between structural form, processing technologies and construction process; architecture and structural form; and materials and structural form. I have generally approached this subject by searching for quantifiable facts and events that explain those developments. However, I base my definition of *material-adapted form* in **Chapter 05** on this information and philosophical arguments.

Since structural form is the main subject of my thesis, any existing research similar to mine would be found in this section of the state of the art. Most works on form do not deal with the specifics of all of the influences on the development of form that I have identified in this thesis. However, Bjørn Normann Sandaker's 2000 dissertation *Reflections on Span and Space* and Rowland J. Mainstone's *Developments in Structural Form*, first published in 1975, do examine similar themes as I do in this thesis. I will separately examine the parallels and differences between these works and my own at the end of this chapter.

2.4.2 Philosophy of Form

Books on the philosophy of form such as Horatio Greenough's *Form and Function* and Christopher Alexander's *Notes on the Synthesis of Form* have limited valued in this thesis. Though they are useful towards defining a philosophy of form, they do not address the subject of structural form with adequate specificity. In interesting area of exploration is the application of knowledge about natural form for generating man-made forms. D'Arcy Wentworth Thompson's *On Growth and Form*, first published in 1917, is perhaps the best known reference on this subject and is of great value towards this direction of inquiry even though some of his conclusions have been found to be incorrect. An abridged version of his book was first published in 1961, which had a greater impact than Thomson's original book that was 800 pages long in 1917 and over a thousand pages when the second edition was published in 1942. The influence of the Thomson's book is apparent in Lancelot Law Whyte's *Aspects of Form: A Symposium on Form in Nature and Art*, which is a collection of papers examining the relationship between natural and man-made form in art (1951).

Various engineers have drawn inspiration from natural structural forms. Some notable engineers that have explored this relationship are Robert Le Ricolais, Buckminster Fuller, Frei Otto, and J.E. Gordon. I do not consider the subject of natural form – man-made form.

2.4.3 Processing Technologies, Construction Process and Structural Form

Peter McCleary studied the relationship between processing technologies and form in an undated paper entitled "The Role of Technology in Architecture." McCleary examines the aesthetic differences of two libraries in Paris designed by Henri Labrouste, the Ste.-Geneviève and National Libraries. These libraries were constructed of cast iron and wrought iron respectively. This thesis explores this relationship further, but there is clearly a need for more research to be done in this area.

Tom F. Peters, Robert Mark, and James Strike have variously examined the role of construction process in design and its influence on form. In *Building the Nineteenth Century*, Peters provides a comprehensive analysis of the long-term effect construction process has had on design and technological thought. Mark's book, *Architectural Technology up to the Scientific Revolution* (1993), is a good overview of the historical development of stone construction. His book explains how construction concerns influenced the development of arch, vault, and dome forms. Strike examines in detail the influence of prefabrication and modular building systems on design. Gevork Hartoonian examines the influence of construction in architectural design more philosophically in his book *Ontology of Construction* (1994). Peters' work is more articulate.

2.4.4 Structure, Architecture, and Form

Numerous sources address the topic of structural form. Most of these sources approach the subject from an architectural perspective. In *Structure and Form in Modern Architecture* (1975), Curt Siegel considers the problems of structural form in modern architecture. He proposes a theory of criticism of architecture that relates the aesthetic clarity of structural expression or appropriateness to construction process and method. Moshe Safdi's *Form & Purpose* (1982) has little to do with structure or its architectural expression. It is about how poorly architects create place. In *Structure and Texture* (1976), Werner Blaser studies the relationship between structural tectonics and aesthetics. The book is primarily pictographic with little explanatory text, but the images shown comprise a powerful and compelling study of structure and aesthetics.

David Billington presents an engineer's perspective towards the development of a philosophy of structural aesthetics in his book *The Tower and the Bridge* (1983). He chronicles the development of the 'structural artist' from Thomas Telford to Fazlur Kahn. Billington shows how the ideas of efficiency and economy are not without the capacity to achieve aesthetic beauty. Conversely, these qualities drive the generation of structural art. The aesthetic quality of process is a theme recurring in Tom F. Peters' writings. All of these qualities must, however, be balanced by the less apparent search for what Billington refers to as "engineering elegance."

2.4.5 Material, Structure, and Form

The relationship between material properties, structure, and form has been extensively considered from a number of different perspectives.

Heino Engel takes a 'material-less' approach in his book *Structure Systems* (1997). Engel presents a comprehensive, visual approach to structural conception based on a typology of structural systems. Engel's work can be a powerful tool in conceptual design that disassociates the design process, however briefly, from materials. I incorporate Engel's model into the form-finding process defined in **Chapter 04**.

Several famous architects, such as Eugène-Emmanuel Viollet-le-Duc, Frank Lloyd Wright, and Louis I. Kahn have put forward the idea that materials have a *nature*. This nature in some way determines what forms and applications a material is particularly suited for. Italian engineer Pier Luigi Nervi echoes the idea of a nature. Nervi and Spanish engineer Eduardo Torroja, both eminent engineers of reinforced concrete structures, wrote on the relationships between material, construction process, function and structural form. Their work challenged conventions and perceptions of material and form, and remains fresh and daring even today. **Chapter 05** incorporates the writings of these architects and engineers to help define what the nature of a material actually means and how it relates to material-adapted form.

Finally, two sources that are particularly close in content to my thesis are Bjørn Normann Sandaker's *Reflections on Span and Space: Towards a Theory of Criticism of Architectural Structures* (2000), and Rowland J. Mainstone's *Developments in Structural Form* (1998). Sandaker attempts to deal with complexity of form finding as a means of developing a theory of criticism for structures. Mainstone's book is much more of a catalog of structural development, however he does begin to analyze the influences on the origin of new form at the beginning and end of his book. I will examine each in more detail below.

2.5 Sandaker

Bjørn Normann Sandaker's purpose in writing *Reflections on Span and Space* is to develop a theory of criticism for architectural structures. This is the first important distinction between his work and mine. When Sandaker speaks of form, his arguments are within the context of form as an aesthetic entity. Sandaker subordinates the extents to which structural requirements or technological limitations influence form to being a component of architectural form.[4] In my thesis, the reverse is true. I am approaching the issue of form from a structural perspective. Architectural issues such as aesthetics are but one component of structural form.

Sandaker's arguments about the link between structure and form are limited to statics and geometry. Sandaker states that *strength + stiffness properties = resultant form*.[5] In his section on the relationship between material properties and form, Sandaker does not explain this conclusion.[6] He includes sections that have titles indicating he is examining other influences such as material properties and processing technologies, but his arguments invariably return to the statics and geometry of structural systems. In one instance, Sandaker states, "The efficient use of structural materials means to seek stiffness and strength through geometry rather than through mass and dimension… Structures become more efficient when the members resist loads by setting up axial forces (or surface forces) rather than bending forces."[7] He gives a long list of proscriptive ways to form structures to be more efficient, however, this list is disassociated from material properties.

In another instance, Sandaker states that both steel and wood have similar geometrical qualities. Sandaker does not satisfactorily explain what *geometrical qualities* exactly are, but he reasons that this is why both wood and steel appear in linear and modular form.[8] Steel is isotropic, which means that it could be used 'geometrically' in three dimensions, if we assume a direct correlation between material properties and Sandaker's geometrical properties. Wood is anisotropic with linear fibers and is limited in size by tree growth, thereby justifying its use in linear, modular forms. Disregarding economic arguments for now, steel can hypothetically be produced in any quantity desired, cast-in-place as we do reinforced concrete, and shaped into any form we desire. Sandaker notes that "neither wood nor steel are shaped in [linear and modular forms] as a necessity for employing them structurally, but a *possibility* (emphasis Sandaker) among others chosen for other reasons," but he does not adequately explain how or why particular forms are chosen.

Sandaker states that the influences on local form are structural properties, technological properties and geometrical properties. Sandaker classifies the first two influences as mechanical properties that are "unambiguously measurable and numerical."[9] The third influence relates to "what kind of geometrical appearance the structural materials are likely to take."[10] This is a false premise since a material, unless it is biological, cannot *take* any form unless a human conceives of it *and* can process the material into that form. Sandaker examines the question of what the *nature* of a material is. His analysis parallels mine in many ways, including the references used. However, Sandaker never actually commits to defining a more concrete definition of the nature of a material than that provided by Viollet-le-Duc, Wright and Nervi. I address Sandaker's analysis further **Chapter 05**.

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[4] Sandaker, p54.
[5] Sandaker, p38-39.
[6] Sandaker, p59.
[7] Sandaker, p94.
[8] Sandaker, p58.
[9] Sandaker, p60.
[10] Sandaker, p60.

2.6 Mainstone

Rowland J. Mainstone's book, *Developments in Structural Form*, relates to my thesis in subject and scope. Mainstone examines a number of the same influences on the development of structural form that I will cover in **Chapter 04**. However, the scope of his review is rather limited. In the beginning of his book, Mainstone writes: "Development is… a historical process. New developments build upon those that went before. But there are so many cross-currents, borrowings, influences, and interactions that there is no single linear progression."[11] He does not attempt to analyze these influences and their interactions as I have attempted to do in this thesis.

Mainstone does address the influences of function, construction process, and knowledge as they pertain to the development of form. Some similarities exist between his work and my analysis in **Chapter 04**. His compilation of structural forms and their development reads as much like a history of human civilization and its development of civic ritual and habit as it does about the structures themselves. Mainstone's figures clearly illustrate how the development of architectural forms for churches and civic buildings, as well as infrastructure such as railroad stations and bridges, demanded that structure encompass more space, span farther distances and carry heavier loads.

Mainstone emphasizes the importance of analysis, geometry and statics and how this knowledge gave designers more 'choice' to create structural form. His unstated thesis seems to be that without the intellectual tools to justify a form – to intuitively understand how a form transfers stress – the mind could not first conceive of it.

Mainstone does not really address the form relationship at all in his chapter on the relationship between material properties and form. Instead, Mainstone gives a good, basic description of the properties of various structural materials and states what applications these materials are good for. This prescriptive method of assigning appropriate applications and forms to specific materials is only disparately supported in the main body of his the text where the focus is overwhelmingly on geometric form and its relation to statics.

For Mainstone, the principal influence on form is statics. He writes, "The overriding requirements governing the choice of form for the complete structure are geometrical ones concerning the relative disposition of elements in space. With the wide choices of materials, internal details and methods of construction available today, these are not usually onerous requirements."[12] Mainstone is more concerned with the effects of form on *material choice* rather than the development of forms for specific materials, an objective of this thesis.

As a resource, Mainstone's book is complementary to my thesis and I recommend consulting it. It is an excellent, broad record of structural development. The illustrations clearly show how materials and structural form have developed through history, but Mainstone does not explore the link between the two in sufficient detail. The quality of the book is further diminished by Mainstone's heavy use of conjecture and his disappointing final chapter on design, which ends with the unsubstantiated conclusion that intuition and judgment are the keys to creating new structural form.

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[11] Mainstone, p29.
[12] Mainstone, p94.

2.7 The Contribution of this Thesis

This thesis builds upon and adds to the state of the art in a variety of ways. No single source attempts to comprehensively identify the influences on the creation of structural form and the development of structural materials as this thesis does. Mainstone and Sandaker variously attempt to make such lists. Mainstone makes many assumptions that I examine, though his are either incorrect or at least incomplete. Though Sandaker uses vocabulary similar to mine with respect to structural hierarchies, he formulates his arguments poorly. His concepts related to that vocabulary are unclear.

This thesis attempts to present a comprehensive catalog of influences, thus it is necessarily broad in scope. Some aspects are focused upon more than others, however this catalog provides a framework upon which to build. To the knowledge of the author, the methodology of form-finding presented in **Chapter 04** is original. It is different from other design methods because it is structured around a hierarchical classification of form described by Ideal Form, Constructible Form, and Implemented Form. Other models are distinguished by prescriptive methods that are focused on the product. My model focuses on process and provides a method to evaluate form-finding techniques for structures.

The case studies on technological history build on known and secondary sources. I review these histories in an independent way. Existing histories either focus on the technical details of a particular structure, as typical of articles in *Transactions of the Newcomen Society*, or focus on the contextual or cultural issues, as found in *Technology and Culture*. The case studies of this thesis are an attempt to combine both approaches. Additionally, the case studies include issues of technological thought and method, which is not commonly found in either *Technology & Culture* or *in Transactions of the Newcomen Society*. Most catalogs of structural forms are chronologically based. My case studies attempt to look at antecedents, the knowledge available at the time of conception, socio-economic context, and what the persons involved were thinking at the time. Such a view is important to understanding not only developments as they actually occurred, but also to highlight contextual differences between developments in the past and today with respect to time, demographics, geography and culture. Furthermore, the material in the case studies on airships, aluminum, plywood and FRP begins to address the lack of material available about those subjects.

Concerning the philosophy of form, this thesis addresses deficiencies in the writings of eminent architects and engineers such as Eugène-Emmanuel Viollet-le-Duc, Frank Lloyd Wright, Pier Luigi Nervi and Louis Kahn about the so-called *nature* of built form. Their writings lack a clear definition of what the nature is and how that definition translates into form. This thesis attempts to redress that deficiency. Additionally, this thesis addresses the issue of substitution in the development of new structural materials. Substitution is widely understood to constitute an initial phase in material development that is viewed negatively. There is an assumption that new materials used substitutionally are unthinkingly used in the place of another material with little regard for the new material's unique properties. This view of substitution will be shown false. A new interpretation is presented that argues for a more positive view towards the value of substitution in material development.

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STRUCTURAL FORM

03

3.1 Structure

In construction, a structure principally receives, transfers and discharges loads while providing a framework upon and within which to support a given function.

The most important requirement of structure is that it ensures *structural security*. Structures are subject to different stresses – tension, compression, moment, shear, torsion and fatigue. These stresses are caused by static and dynamic loads classified under three general categories: dead load, live load and dynamic load. Basic geometrical, strength and stiffness requirements ensure the security of a structure by maintaining structural stability when subject to specified load conditions.

A bridge or building structure must also satisfy *serviceability requirements*, which can be structural and non-structural. The chief structural requirement is to control the amount of deflection and vibration a structure is subject to under design loads. Non-structural requirements are related to a material's thermal and acoustic properties, electric conductivity, and resistance to corrosion and other degradation.

Fig. 3.1: Prefabricated aluminum house. The corrugated aluminum panels are both structure and environmental barrier. (London Northern Aluminum)

Finally, a structure may have to serve a secondary function in the constructed artifact, which is called *function integration*. Examples of function integration are when a structure must also serve as an environmental barrier, such as in the corrugated aluminum house shown in **Figure 3.1**, or when the structure must also transmit light, made possible by using structural materials such as glass fiber reinforced polymer sandwich panels or translucent concrete. (**Figs. 3.2 and 3.3**) While the principal focus of this thesis is on structural form, the issue of function integration is too important to ignore when analyzing the historical development of structural forms and when designing today, especially with fiber reinforced polymer composites (FRP). Function integration is examined in more detail throughout this thesis.

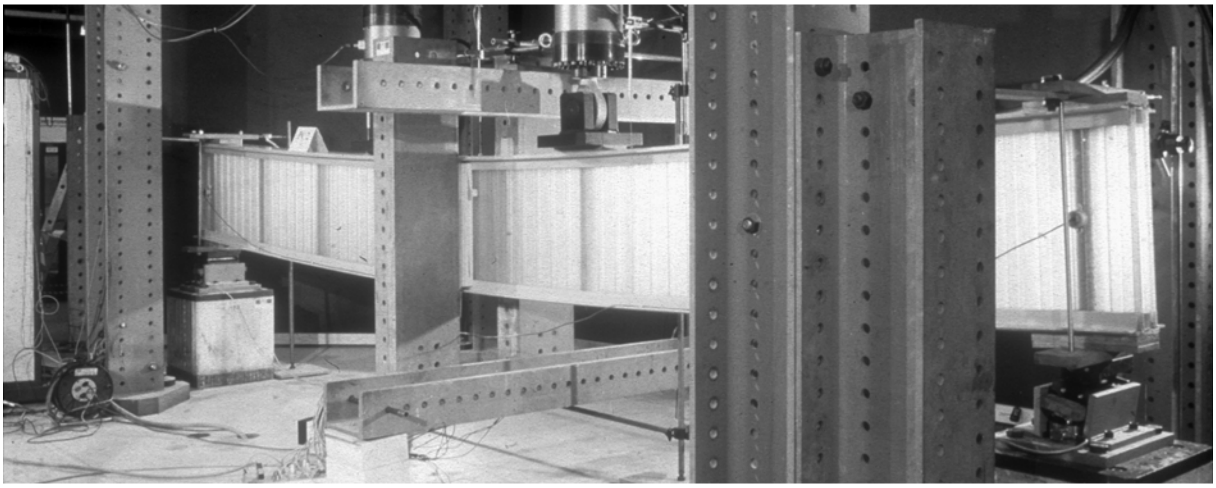

Fig. 3.2: GFRP girder with translucent sandwich panel web. (CCLab)

3.2 Hierarchy of Structural Form

3.2.1 Two Hierarchies

Two hierarchies of structural form are used in this thesis. The first classifies structural form as being *Global* or *Local*. This hierarchy is used in other references, including Bjørn Normann Sandaker's dissertation discussed in **Section 2.5**. This classification system is of limited use because it does not adequately describe the multiple levels of form that are generally grouped under Local Form. Therefore, I have created my own classification with the categories of *Structural Systems*, *Components*, *Elements*, and *Details*. These can also be referred to as *System Form*, *Component Form* and so on. I derived this classification system independently, but my categorized definition of System Form is taken directly for the book of the American architectural professor, Heino Engel, titled *Structure Systems*. All other definitions are my own. I propose using Engel's work as a tool in the form-finding process at the end of **Chapter 04**, but only as it relates to the conception of System Form.

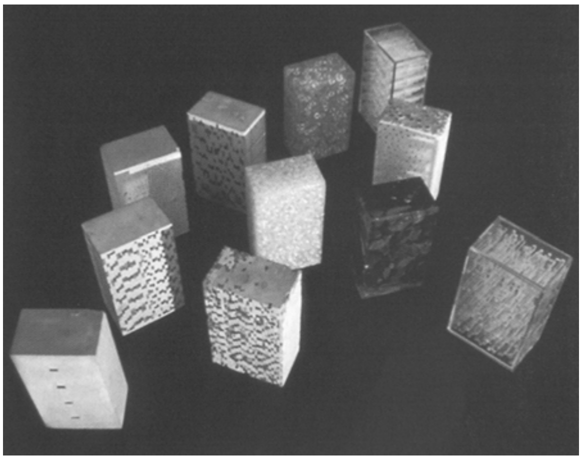

Fig. 3.3: Sample of translucent concrete developed by Bill Price. (Ivy)

Fig. 3.4: Schematic of a two-hinge arch. (Dooley)

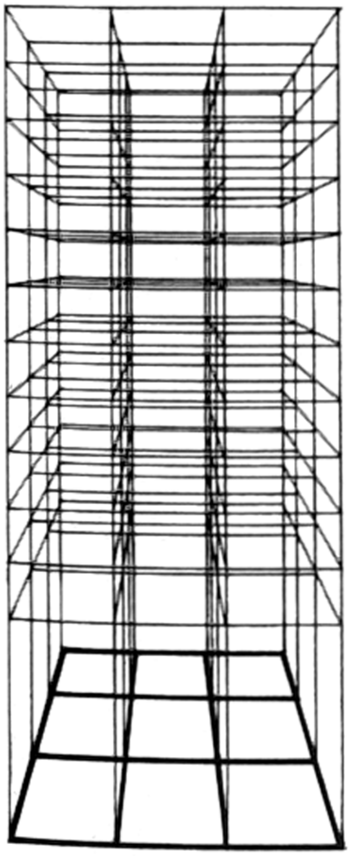

Fig. 3.5: Schematic of a building frame. (Engel)

3.2.2 Structural Systems and Global Form

Structural Systems are complete structural models with inherent structural stability that satisfy function-defined requirements for enclosing or spanning space. A system defines the *Global Form* of a structure, such as the two-hinged arch, or building frame shown in **Figures 3.4 and 3.5**. Systems can be designed from the laws of mechanics and geometry in the absence of a defined material or material properties. Therefore, Systems are not conceptually bound to the present state of knowledge of materials, processing and construction.

The cable-supported roof shown in **Figure 3.6** is an example of a non-material System model. This figure comes from Heino Engel's book, *Structure Systems*. In this book, Engel defines a System to be a *design principle*, which cannot be incorporated into a design without further test. In this thesis, a System is a model from which a designer or developer defines parameters to determine the suitability or applicability of particular materials to build the structure.

Engel's book provides a useful typology of structural systems. This typology could be used as a basis from which to determine general categories of material-adapted forms for specific materials. Engel groups structural systems into the following five categories plus a separate category for hybrid systems:[1]

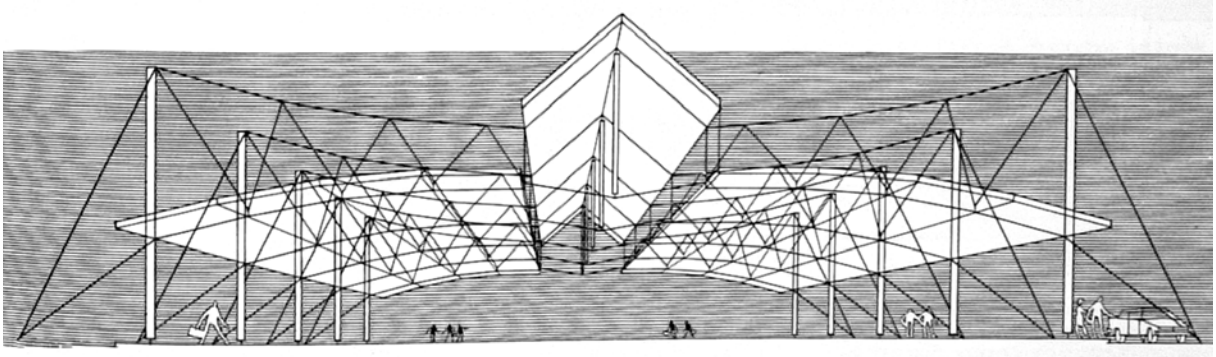

Fig. 3.6: Wire and surface model of a cable supported roof. The model is not material specific. (Engel)

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[1] Engel, p20 and 320.

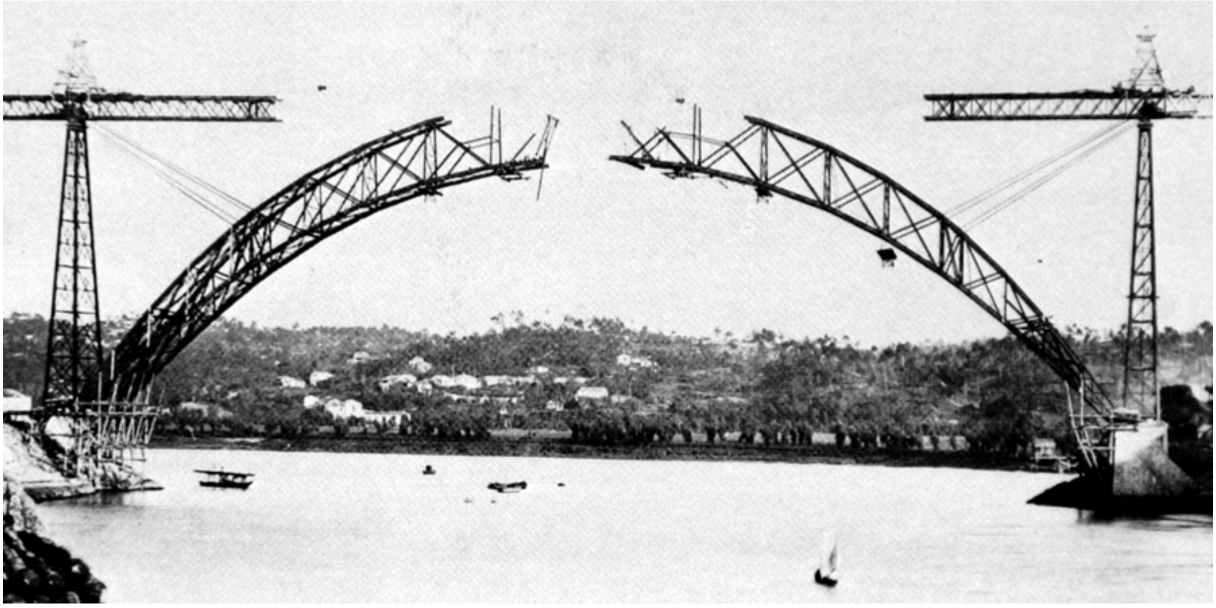

Fig. 3.7: Pont sur le Douro, under construction. Gustave Eiffel, 1877, Porto, Portugal. (Loyrette)

Form-Active Structure Systems

Form-Active structures adjust to the forces, acting mainly through material form. Such systems are in a condition of single stress, subject to either compressive *or* tensile forces. Arch, tent, cable and pneumatic structures are types of Form-Active Structure Systems.

Vector-Active Structure Systems

Vector-Active structures dissect forces, acting mainly through a composition of compressive and tensile members. Such systems are in a coactive stress condition, subject to both compressive and tensile forces. Flat trusses, curved trusses and space trusses are types of Vector-Active Structure Systems.

Section-Active Structure Systems

Section-Active structures confine forces, acting mainly through cross section and continuity of material. Such systems are in a bending stress condition, subject to forces generating internal moment and shear stress. Beam, beam grid, frame and slab structures are types of Section-Active Structure Systems.

Surface-Active Structure Systems

Surface-Active structures disperse forces acting mainly through extension and form of surface. Such systems are in a surface stress condition, subject to membrane forces. Shells, plate, and folded plate structures are types of Surface-Active Structure Systems.

Height-Active Structure Systems

Height-Active structures collect and ground forces, acting mainly to transmit vertical load. Such systems do not have a typical stress condition. Bay-type, casing, core, and bridge high-rises are types of Height-Active Structure Systems.

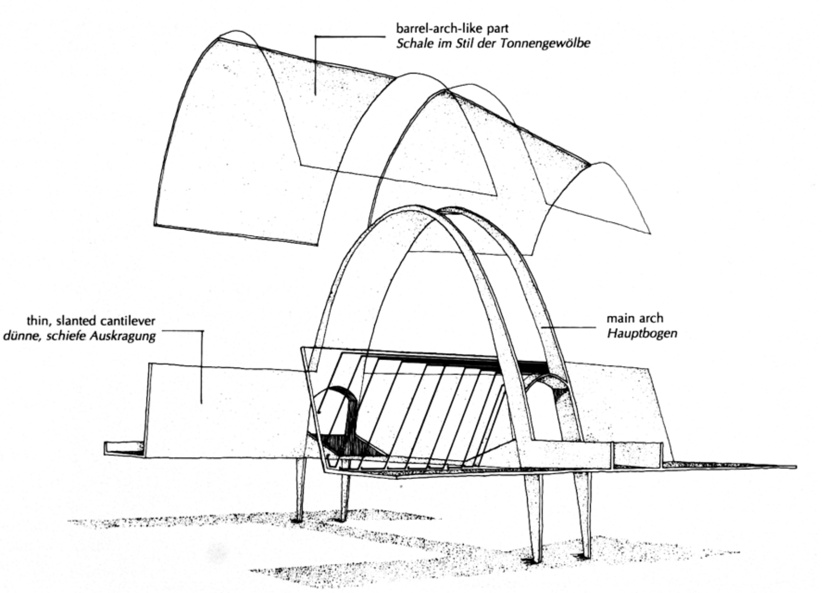

Fig. 3.8: Cement Hall, early reinforced-concrete thin shell. Image shows arrangement of reinforcement in the shell. Robert Maillart, 1937, Zurich. (Billington)

Hybrid Structure Systems

> Hybrid structures are composed of two structural systems with dissimilar mechanics for redirecting forces. When the two systems are combined, a new, hybrid system is created. Superimposing or coupling two systems makes a hybrid system. Engel does not consider a hybrid system as being a unique or characteristic structure type because they do no possess an inherent mechanism for redirection of forces, develop a specific condition of acting forces or stresses, or command structural features characteristic to them.

Examples of Engel's typology for each system-type are copied in **Appendix A-07**.

I include Engel's structural typology, which only applies to System Form, as a tool of form-finding at the end of **Chapter 04**. An important distinction between my work and Engel's is that Engel has created his typology of structure in the absence of function and material. This thesis is based on historical examples of structure that have been realized with specific functional purpose. Caution should be used in relying on Engel's typology since there is no reason to accept his system as comprehensive and complete. Developments in materials, processing technologies, general knowledge of structural theory, or simply a historically original design problem, can lead to the invention of a new structural system. While Engel's examples are restricted to building types, it can be equally applied to bridges and other engineering structures.

3.2.3 Structural Components and Local Form

Structural Components are the parts that make up a System. For example: if the above-mentioned two-hinge arch were part of Gustave Eiffel's Douro Bridge located near Porto, Portugal, then the trussed bars of wrought iron would constitute the Components of the System. (**Fig. 3.7**) If the arch were made of reinforced concrete with a box section, then the chords and sidewalls would be the Components. The case of an arch with a solid section subject only to axial compression constitutes an example of a Component that is also the System. However, the same is not true for most reinforced concrete shells, which I initially presumed to fall into this Component as System category. The uniform, outward appearance (of well designed shells) often belies the fact that the shell is actually composed of elements with different structural functions. A ‘pure’ shell would only transmit compression and be subject to hoop stresses. However, shells with apertures or free edges need compression or tension rings, and stiffening edge or transfer beams. The drawing of Robert Maillart’s Cement Hall, shown in Figure 3.8, clearly shows different structural components – vault, cantilevered transfer beams within the section of the vault, and edge beams, which are only discerned by revealing the placement of the reinforcing steel.

Local Form is a combination of geometric form derived from mechanics influenced by a material’s structural properties, and processing and constructive attributes.

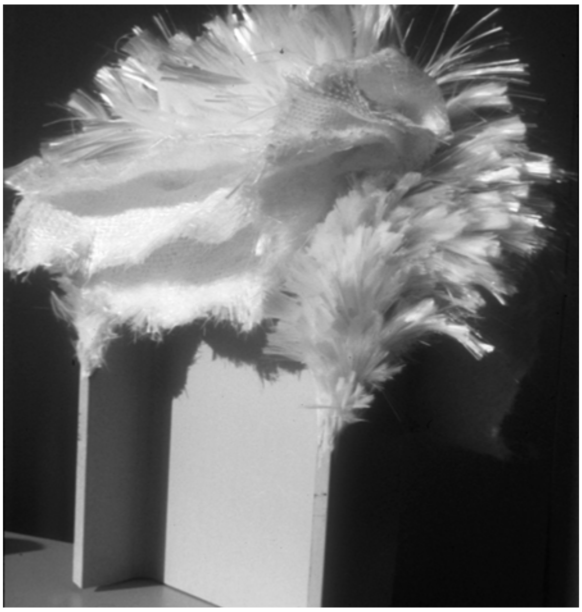

Fig. 3.9: Pultruded GFRP I-section with fiber mats showing. (CCLab)

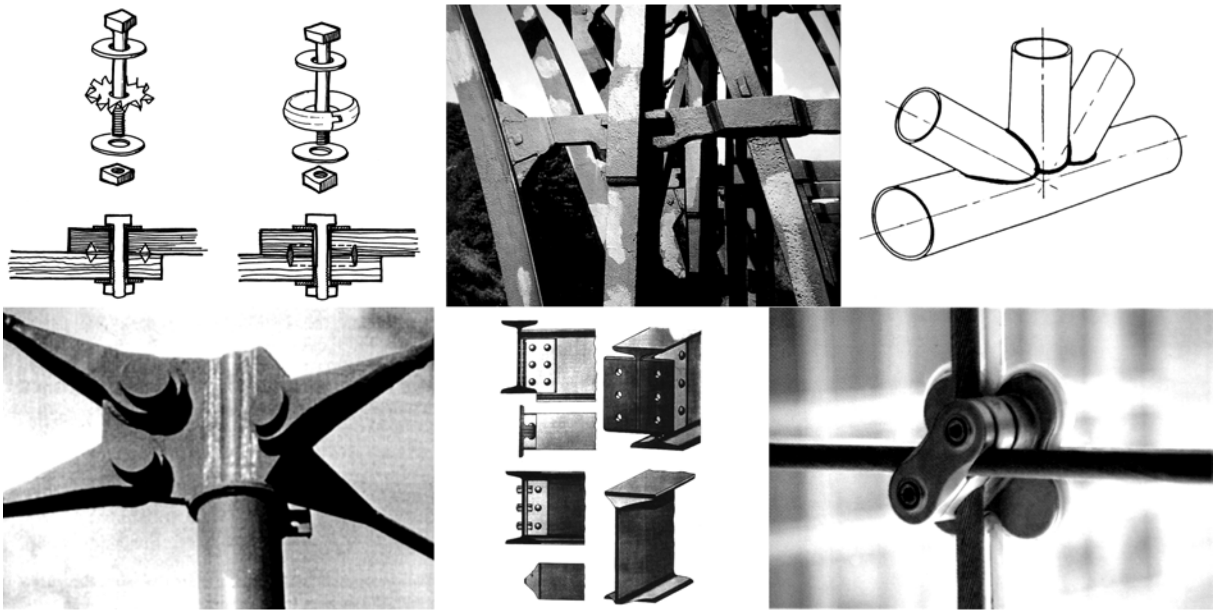

Fig. 3.10: Structural Details, clockwise from top-left: clamping plate and split-ring timber connections (Sealy); pinned and wedged connections of cast-iron Ironbridge, 1779 (Brown); Welded node of tubular steel truss (Blanc and McEvoy); Cable-net node (Holgate); Typical steel beam connections (Yeomans); Tension rod – mast connection (Blanc and McEvoy).

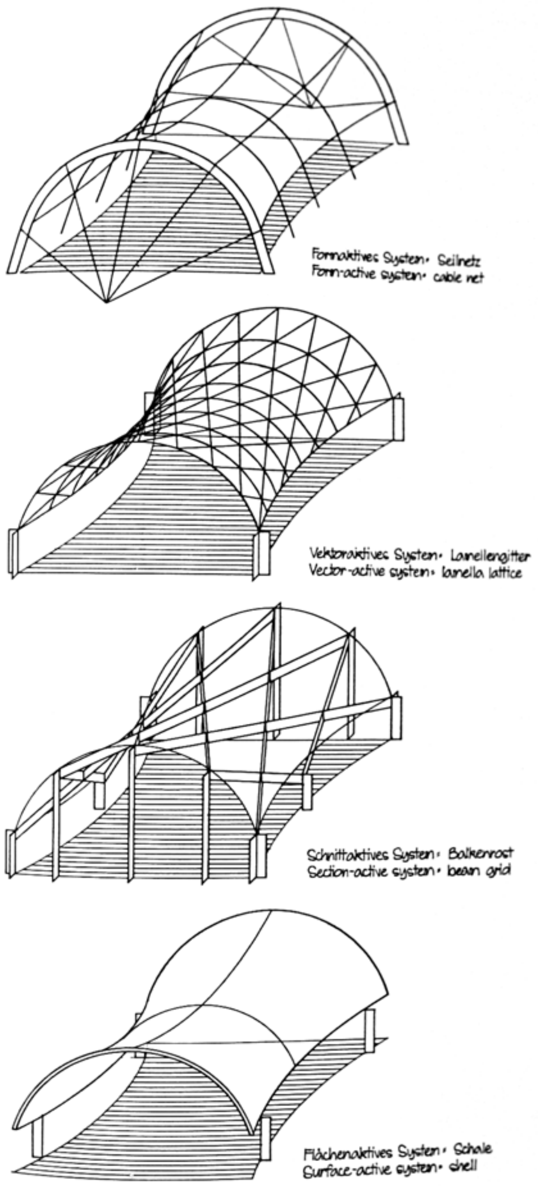

Fig. 3.11: Composition of four variant Component types to construct a similar System type. The first is a form-active system, the second is vector-active, the third is section-active, and the last is a surface-active system. (Engel)

3.2.4 Structural Elements and Material Architecture

Structural Elements are the constituent parts of composite materials. The geometric arrangement of those Elements is described as *Material Architecture*. Material Architecture can also be used to describe the microstructure of homogeneous materials such as metals. There is a direct relationship between material architecture and a composite material's structural behavior, as evidenced by the design of reinforcement for concrete, or the characteristics of different fibers and their use as strands, mats and textiles in FRP materials. (**Fig. 3.9**) Composite materials offer the possibility to alter a material's structural properties, which gives the designer more power to optimize structure, even though the outward Global and Local Forms remain the same. In an FRP **I**-section, the fibers can be orientated longitudinally in the flanges for axial stress and in different directions in the webs to transmit shear stress more efficiently.

3.2.5 Structural Details and Detail Form

Examples of *Structural Details* are connections, joints, bearings, stiffeners, hangers, saddles, anchors and base plates. (**Fig. 3.10**) Detail form is arguably more material specific than other levels of structural form. Details often require a different material than the base material of the structure, especially for non-metals, because of stress concentrations. Steel is the most frequently applied connecting material because of its excellent toughness, ductility, and stiffness.

In this thesis, I am primarily interested in the relationship between System, Component and Element form to material properties, and how those forms have historically evolved. Detail form, generally treated as a separate art in structural design, will only briefly be addressed in **Section 4.5**, *Connection Technology*.

3.3 Form Types

3.3.1 Introduction

This thesis introduces a concept of Form Types that are classified as being: Ideal$_1$, Ideal$_2$, Constructible and Implemented. I created these Form Types in order to develop a rational conceptual model of form-finding. This model, the Form-Finding Influence Interaction Model, is presented at the end of **Chapter 04**. I have found no record of an existing design process model that is structured around a similar classification system.

3.3.2 Ideal$_1$ Form

Ideal$_1$ Form is a System Form Model derived from the structural and functional parameters of a project. Those parameters include: the volume of space that must be enclosed or the expanse of space that must be traversed; load conditions; the limits on where and how the imposed load can be discharged; and serviceability. The objective is to design the most structurally efficient System using statics and structural theory, which can be done without regard for specific material properties. The resulting model can be described by a wire frame and surface diagram similar to that shown in **Figure 3.6**.

Engel's typology of Structural Systems can be used as tool of design to define the Ideal Form because his system is conceived of without consideration, and the attendant limits, of specific material properties.

3.3.3 Ideal$_2$ Form

Ideal$_2$ Form leads to the development of Component and Element Form by the application of specific material properties. In the form-finding process, a material would either have to be chosen to best suit the Structural System of the Ideal$_1$ Form, or a pre-determined material would have to be adapted directly to the System. The objective is to optimize material usage, thereby using the least mass of material. The conception of Ideal Form is not limited by technological limitations of fabrication and construction, or cost.

Engel's model can also be a useful tool to inform material choice for the designer, and the conception of Component Form for the developer. **Figure 3.11** shows an example of a Structural System from Engel in which different components are used, each variant clearly exhibiting properties that would encourage the use of one material versus another, or, in the case of the developer, one Component Form model over another. This figure illustrates the great flexibility a designer has to adapt different materials to different Systems, or, conversely, the System to the material.

The Ideal$_2$ Form is a combination of the Function Parameters, the Structural System, and Material Properties. It is tempting to restrict this definition further to include only *structural* properties, but the Function Pattern includes Function Integration. Therefore, the form-finding phase generating the Ideal$_2$ Form can result in one of two outcomes, a *Structural Ideal Form*, or an *Integrated Ideal Form*. *Structural Ideal Form* is that which best exploits a material's combination of structural properties while satisfying function requirements. The Structural Ideal Form is a minimum-material structure. The *Integrated Ideal Form* is generated by function integration and is a minimum material building system. The difference from the Structural Ideal is that the Integrated Ideal Form may be less structurally efficient than if the structure had only to serve its primary purpose of receiving, transmitting, and discharging load. While there may be excessive material from a structural perspective, the objective would be net material efficiency and part-count reduction when the building system as a whole is considered.

3.3.4 Constructible Form

Constructible Form is structural form that can actually be produced using existing material processing technologies, connection technologies, and construction process and methods. The objective is to make Ideal Form producible. Cost is the only limit not considered in the conception of Constructible Form. The process of defining Constructible Form allows technologies to be identified that lack for producing Ideal Form. The process also gives the developer the opportunity to identify particularly expensive processes, technologies or construction techniques that make it cost prohibitive to use the most materially efficient structural forms.

3.3.5 Implemented Form

Implemented Form is the structural form actually used in practice. Economics is generally the ultimate driving factor in determining what form is constructed. Therefore, the Implemented Form is the product of choice. The choices are defined by what is Constructible. Cost is rarely an insignificant influence in practice; possible exceptions being cultural or experimental projects, though even these will likely have budgets to respect. Since projects in which cost is no object are rare in practice, I will not consider them further.

The Britannia Bridge case study records how the designers debated the merits of using circular or rectangular cells to make the flanges of the tubular beam. (**Appendix A-03, p.A.126, Figs. 58 and 59**). Experiments had shown that the circular cells would be more structurally efficient and resist buckling better. Rectangular cells were simpler to fabricate, and the designers felt that there were less potential problems with corrosion because the rectangular cells could be more easily inspected for water infiltration. Since the rectangular cells adequately resisted buckling, there was no justification for the additional cost to fabricate circular cells that also presented maintenance problems. In this example, the less efficient Implemented Form was chosen because of constructive and serviceability issues. Detail Form was an important factor in that decision because water tightness could not be assured using the riveted connections then used.[2]

The next chapter will analyze the influences on the development of structural form in more detail. This analysis will give greater understanding about the influences that affect the choices leading to Implemented Forms. Since this thesis is based on historical case studies of Implemented Forms, such forms are important to the analysis of material development and my overall conclusions.

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[2] **Ref. Appendix A-03, p.A.126-A.127**.

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INFLUENCES ON THE DEVELOPMENT OF STRUCTURAL FORM

04

4.1 Introduction

4.1.1 The Influence Categories

This chapter examines various influences on the development of structural materials and form. The development of structural materials is closely linked to the development of structural form. This section will consider both aspects. The influences are:

- *Function*
- *Material Properties*
- *Processing Technologies*
- *Connection Technology*
- *Construction Process*
- *Economics*
- *Socio-Political Factors*
- *Knowledge*
- *Technological Thought*

The review of these influences is broad in scope. The intention is to provide a comprehensive explanation for the development of structural form and, relatedly, the general development of structural materials. This chapter concludes with a Form-Finding Influence Interaction Model that addresses how the various influences are interrelated and summarizes their role in the form-finding process.

4.1.2 Origin of the Categories

The influence categories reflect observations made from the historical record. No singular reference can be cited that led to the development of this list. The evidence supporting this list of influence categories is explicitly presented in the various examples used throughout this chapter. The case studies reflect the raw data that led to the formation of the list.

When this project began, the influence list began as a series of questions that probed the role of different factors in the process of form-finding. Those factors are:

- The role of education
- The role of precedent
- The role of established materials

- The role of aesthetics / proportion
- The role of materials science
- The role of construction methods
- The role of fabrication methods
- The role of statics / mathematics
- The role of society / politics
- The role of visual education

This list reflects my early focus on technological thought. However, this path of inquiry is too subjective, and does not adequately address the global objective of creating a comprehensive influence model. It contains the rudiments of the list that later emerged. This approach demands more in-depth research, and requires a case study for which excellent primary source material exists. I had considered making such a study on the Zeppelin airships. However, the depth of research required would have precluded making other case studies in either the quantity or depth that I have. Such a narrow focus on one case study is too limiting. Little confidence could be had in whether the trends of development identified in one study were representative of the development of other structures and materials. The interaction of influences could vary widely from one historical example to another, as one would expect the parameters and influences of design to differ between the design of Greek temples and the design of the Britannia Bridge.[1]

The decision to make a wider historical study led to a more definite list of influences. The first list included the following categories:

- Material Properties
- Material Manipulation Technologies
- Connection Technologies
- Economics
- Socio-Economic Factors (including political)
- Knowledge of Structural Theory and Analysis
- Education
- Technological Thought

The major omissions of this list in comparison to the final list in **Section 4.1.1** are Function and Construction Process. When this list was made, I accepted Function as a given without defining what was meant by it or understanding its role in conceptual design. In effect, Function seemed so obvious that it did not warrant further discussion. I included Construction Process in the category Material Manipulation Technologies, defined to include *all* processes necessary to take a raw material and put it in its final form and position in a structure. Construction Process became a distinct category based on the fact that Construction Process does not necessarily include forming the material. Organizational,

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[1] **Appendices A-01 and A-03**.

cultural and economic factors are also important factors affecting the influence of Construction Process on form-finding.

The influence of economics is not satisfactorily distinguished in this list. I accounted for so-called *direct* economic costs – which include material, fabrication, and construction – in a category separate from so-called *indirect* costs incurred due to cultural and political influences. Economics is a distinct category in the final list that allows collation and analysis of all economic factors.

Finally, my definition of knowledge evolved from one restricted to structural knowledge to one that is more holistic. This approach accounts for the fact that non-structural factors such as clearance heights are important parameters in conceptual design. Education becomes a cross-category factor as it not only contributes to the dissemination of knowledge, but also influences the development of technological thought. Such cross-category factors warrant further research to analyze the interrelationships between the various influences. In general, more in-depth research of each influence needs to be done to better understand the mechanisms that relate the influences to each other and the socio-economic conditions that enable innovation.

4.2 Function

4.2.1 Function Patterns

Structures support functions. These functions determine the parameters by which a structure is designed. All of the parameters can be grouped together to form a Function Pattern. This pattern defines: the space a structure must enclose or span; performance requirements with respect to loading and serviceability during and after construction; limits for placing load discharge points; and any secondary functions a structure is expected to accommodate. Function Patterns make the relationship between load, program, and architectural expression explicit, connecting these elements to the conception of structural form. This section describes different criteria that comprise the Function Pattern and how Function influences the development of structural form.

4.2.2 Program

A program defines the use of space and the amount of space that needs to be enclosed or spanned. Additionally, the program determines what loads a structure will be subject to because of imposed dead and live loads. These are the most basic parameters influencing structural form, and are part of the *In-Service Program*. The In-Service Program limits the number and placement of load discharge points. For example, the load of a train shed can only be discharged to the sides of the station as a whole and through intermediary points located on the station platforms.

The program need not be restricted to in-service conditions. A program can, and *should*, consider the construction process, the possibility of future alterations or expansion, and the ultimate dismantling of a structure. Respectively, I call these programs the *Construction Program*, the *Future Program*, and the *Post-Design Life Program*.

The *Construction Program* addresses the stability of the incomplete structure, the use of structure to support construction equipment, and the tailoring of structural systems to local construction practices. Construction process, characterized by methods and sequence of that process, can lead to the development of structural systems. In the case of the Crystal Palace in London (1851), the designers had to develop a rational building system they could erect quickly because of time constraints.[2] (**Fig. 4.1**) **Section 4.6** reviews the influence of Construction Process in more detail.

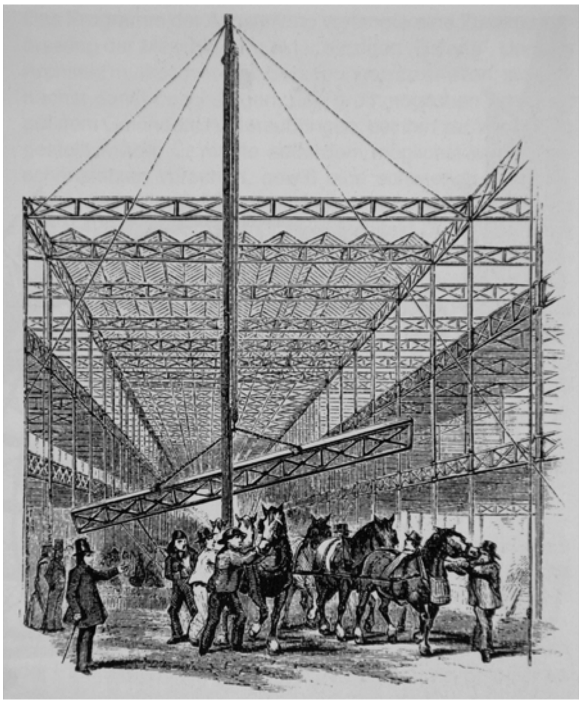

Fig. 4.1: Crystal Palace. Joseph Paxton and Charles Fox, 1851, London.

The *Future Program* considers the future alteration and growth of a facility. Modular building systems like the Crystal Palace or the PA Technology Building, an electronics manufactory in Princeton USA, illustrate this program.[3] (**Fig. 4.2**) The designers designed the structure of the PA Technology Building as a modular system that can be extended lengthwise to accommodate expansion of the production area. The long-span, stayed roof structure accommodates the need for a flexible, column free production space. The mechanical systems are integrated within the open spinal truss to facilitate maintenance.

The Post-Design Life Program is concerned with how a structure is dismantled and disposed of. These parameters will become increasingly important to the design process as design-life thinking becomes more prevalent in conjunction with the growing movement of sustainable development. This type of thinking exists in the automobile industry; manufacturers such as Mercedes-Benz design their vehicles to be fully recyclable. Some materials are eliminated in favor of others because of post-life characteristics because of this type of thinking. Such decisions affect the form-finding process

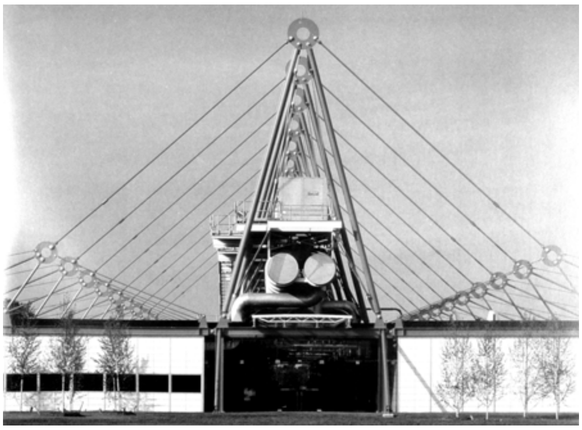

Fig. 4.2: PA Technology Building, modular systems design of manufacturing building. Richard Rogers Parntership with Ove Arup & Partners, 1982, Princeton USA. (Ove Arup & Partners)

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[2] **Ref. Appendix A-05, p A.252-A.254**; Peters[1], p226-254.

[3] Dunster, p253. The PA Technology Building was designed by Richard Rogers in collaboration with engineers Ove Arup & Partners, and completed 1984.

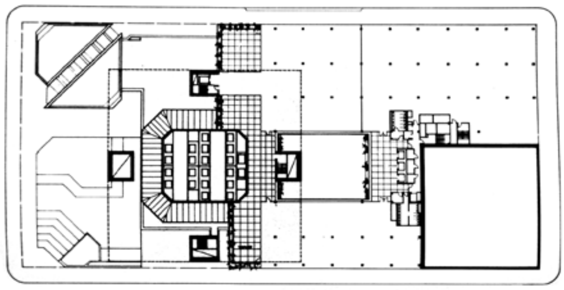

Fig. 4.3: Plan of Citicorp Center, New York City. Church is located in top-left corner of the site. Note that main columns are located at the mid-points of each side of the building. Hugh Stubbins, architect. 1976. (Wagner)

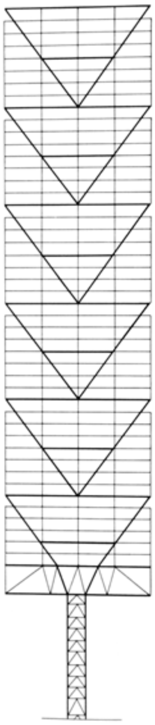

Fig. 4.4: Citicorp building structure designed by William LeMessurier, structural engineer, to accommodate the unusual site constraints. (Wagner)

because these materials may not be the ideal choice for in-service conditions.

4.2.3 Site Constraints

Site Constraints are defined by a construction site's geographic location, geology, existing human infrastructure, climate, and susceptibility to extreme environmental events such as earthquakes and hurricanes. They are included in this section because they are an integral part in defining a Function Pattern before actual design begins. The principal effect of Site Constraints is to limit the location of load discharge points and limit the choice of structural systems. Both parameters are directly linked to the site's geology, topography and existing human infrastructure.

Existing human infrastructure, such as highways, tunnels, archaeological sites, and protected cultural sites can result in the creation of new structural forms. The existence of a church on one corner of a building site in New York influenced the particular design of the Citicorp Building. (**Fig. 4.3**) The church permitted Citicorp to build the skyscraper on the condition that a new church would be built in the same location with no connection to the new building and no columns passing through it. The result is a high-rise building supported on columns located at the center of each side of the rectangular building rather than in the corners.[4] This constraint led the engineer, William LeMessurier, to conceive of a new high-rise structural system that is similar in structure to a tree.[5] (**Fig. 4.4**)

Geology and topography were the principal constraints for the design of a bridge built in New Mexico in the latter half of the nineteenth century. (**Fig. 4.5**) The railroad had to pass through a narrow canyon. The sides of the canyon are close enough to use as supports

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[4] Ref. PBS web site, "Building Big", http://www.pbs.org/wgbh/buildingbig/wonder/structure/citicorp.html

[5] Wagner, p66-71.

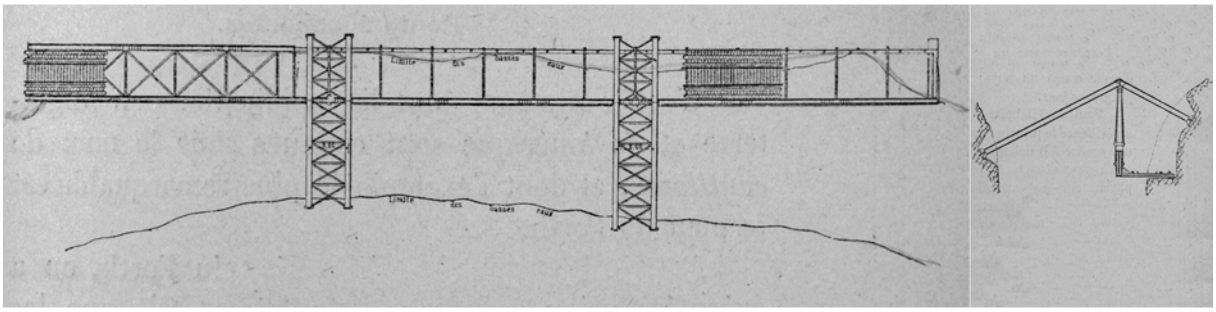

Fig. 4.5: Santa Fe Bridge, Colorado, c.1894. (Le Bris)

even though the train ran parallel to only one side. The bridge is half supported longitudinally along a ledge while a beam suspended from two intermediary frames supports the other half.

Soil conditions can be of particular concern to structural design. Soil conditions limit the number of practical structural systems from which to choose. Poor soils may make it difficult to construct Form Active structures that exert high lateral loads. When Thomas Telford designed the Buildwas Bridge (1795), a cast iron arch structure that crosses the Severn River in England, he superimposed two arches with different rises. (**Appendix A-02, p.A.42, Fig. 18**) Telford designed the deeper arch to principally carry the bridge load and intended the flatter arch to counter any lateral movement by the riverbanks. Telford had observed such a problem just downstream at Ironbridge.[6] (**Appendix A-02, p.A.41, Fig. 17**)

Climate and the possibility of extreme environmental events affect the loads a structure must resist. These loads can affect Detail Form, such as in the case of seismic connections, and System Form, such as in the case of a conceptual design for a new Australian research station in Antarctica. This building was designed to withstand 324 km/h winds and temperatures that range from +5°C to -40°C. (**Fig. 4.6**) The building is designed with FRP materials. The exterior panels are both the structure and the insulated environmental envelope of the building. The main parameters controlling the choice of materials and the pre-fabricated building-panel design were construction and durability issues specific to the harsh climate of Antarctica.[7]

4.2.4 Structural Requirements

Structural Requirements are defined by live, dead, and environmental loads. The location and magnitude of these loads, which can be ordered in the Function Pattern as a *Load Pattern*, are determined by the dead and live loads imposed by the Program, environmental loads associated with a specific site, and the dead load due to the structure's self-weight. Structural Requirements may call for a structure to survive an extreme load event, such as an earthquake or bomb explosion, and ensure the programmatic function can continue immediately after the event.

It is important to consider that while some loading positions are fixed, others can be moved through translation. An example of a fixed load position is a bridge deck. The program and topographic constraints define where the level of the roadway is. Conversely, the height of a roof structure can typically be raised or lowered as desired without changing the actual

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[6] **Ref. Appendix A-02, p.A.41-A.44**.

[7] Brown, p24-27.

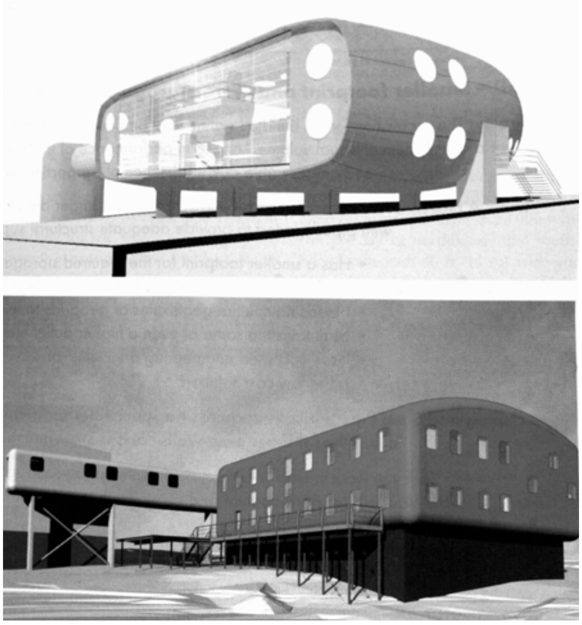

Fig. 4.6: Antarctic Station Design using FRP. Allen Jack + Cottier, 2003. (top) Competition entry. (bottom) Revised design. (Powell)

loading condition. The number of possible structural systems is expanded by the flexibility to control where a load is received by the structure. This freedom should be included in the Function Pattern.

Structural requirements also include serviceability criteria for controlling deflection and vibration caused by the load conditions. The Millennium Bridge, crossing the River Thames at St. Paul's Cathedral in London, closed two days after opening in 2000 because of unexpected lateral movements that were discomfiting to pedestrians. (**Fig. 4.7**) The cause of the problem was the tendency of crowds to walk in lock step. In this case, performance requirements were met by retrofitting the structure with damping devices that did not change the overall form of the Structural System, but did change Component and Detail Form.[8] The structure would be functionally deficient without this remedial action, perhaps necessitating its removal even though it was structurally sound.

Fig. 4.7: Millennium Bridge, London. Norman Foster and Ove Arup & Partners, 2000. (Russell)

4.2.5 Non-Structural Serviceability Requirements

Non-Structural Serviceability Requirements pertain to maintenance and operations issues unrelated to the structure's primary load distribution task. Non-structural serviceability requirements principally affect the *choice* of material and form, rather than directly influence form-finding. The following sections on Material Properties and Processing Technologies could address these requirements. They are included here because they are often parameters that are determined before design begins, therefore constituting a part of the Function Pattern.

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[8] Fitzpatrick; Russell, p78. The Millenium Bridge is an extremely slender suspension bridge designed by the team of architect Sir Norman Foster and engineers Ove Arup & Partners. The central span is 144 m but the cable dip is only 2.3 m, giving a span to dip ration = 63 : 1. Normal suspension bridges have a ratio of 1:10.

Fig. 4.8: Traversina Footbridge: elevation and strut detail. Jürg Conzett, engineer. Viamala, Graubünden, Switzerland. 1999. (Dooley)

One Non-Structural Serviceability Requirement is a structure's durability; here defined as a structure's resistance to corrosion and other forms of degradation. Both material properties and structural form influence durability. Material properties largely govern material choice or the necessity to use secondary materials (paint) or structure (as in the case of covered wood bridges) to protect the primary load-bearing structure. The importance of form is evident in steel structures. Constructive details that prevent water from collecting can limit corrosion. If left unattended, material degradation will eventually result in a significant reduction of the structural section, making what would have been a basic maintenance issue a structural security problem.

Maintenance requirements can directly influence the form of structure. Builders used bulb-tee iron beams in ship construction because its bulbous bottom flange facilitated inspection of the beam for corrosion, especially the inside corner where the bottom flange meets the web. This form also made painting easier.[9] (**Appendix 03, p.A.99, Fig. 29**)

Some structures are designed to facilitate replacing Components that have been damaged or compromised by some form of material degradation. Jürg Conzett, a Swiss engineer, designed the Traversina Footbridge (1997), located in Graubünden, Switzerland, to allow easy replacement of the wood struts of the fishbelly truss. (**Fig. 4.8**) The unprotected struts are each comprised of four separate pieces of timber, each connected separately at the connection nodes. Each piece of the strut can be replaced one at a time without compromising the stability of the structure. The deck of the footpath protects a glue-laminated beam that is the main compression member of the truss.

Other types of non-structural serviceability requirements might include a structure's thermal and acoustic properties. Thermal properties, which are material specific, are important in buildings where it is desirable to minimize the effects of thermal bridges that affect the comfort of occupants and the energy costs of climate control systems. Material properties and form both affect acoustics since both influence the overall harmonic frequency of a structure. Acoustic control is important in theaters or laboratories with vibration sensitive equipment. The electric conductivity of materials can also be important when considering the

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[9] **Ref. Appendix A-03, p.A.100**.

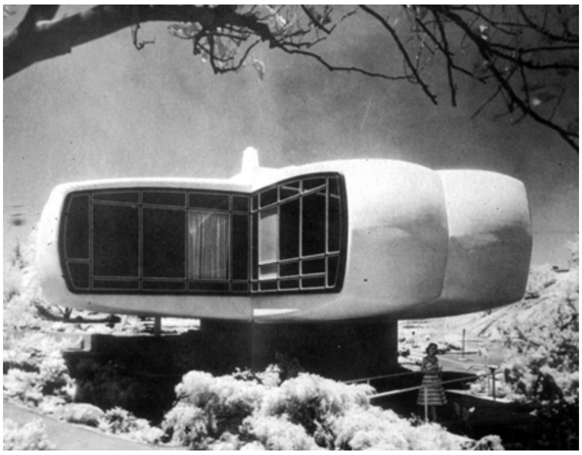

Fig. 4.9: Monsanto Home of the Future, Disney Land. R. Hamilton and M. Goody, 1957. (CCLab)

design of structures for electric generation and distribution systems. Power transmission companies use glass fiber reinforced polymer composite (GFRP) transmission line poles because of not only their lightness and durability, but also their non-conductive properties. The pole's low weight reduces the costs of installation. GFRP poles are more durable than wooden ones, which helps offset their higher initial cost. The non-conductive properties of GFRP poles protect the linemen working on them from electric shock.[10]

4.2.6 Function Integration

This sub-section examines function at another scale than it has been until now. Function here pertains to the purpose of a particular building Component. A Component chiefly defines space as a part in a System and transmits load. However, structure can also be designed to perform or support secondary functions. It should be a conscious objective in design to make each building component perform as many functions as possible. This reduces constructive complexity and maximally exploits the material. This is called *Function Integration*.

There are two types of Function Integration, *integral integration* and *complimentary integration*. Integral integration is when the structural form directly performs a secondary task. Complimentary integration is when the form of the structure is modified to accommodate a separate function made of different components.

Integral integration is being explored for fiber reinforced polymer materials (FRP).[11] Glass fiber reinforced polymers (GFRP) are being developed not only to perform a structural function but also transmit light and create environmental barriers. The translucent beam shown in **Figure 3.2** is an example of how structure can also transmit light into a space. Experimental FRP buildings in the 1960s and 70s, such as the Monsanto House, integrated the structure and the environmental envelope into one building component. (**Fig. 4.9**) Today, foam core sandwich panels or aerogel filled corrugated-core sandwich panels can provide the strength, insulation value, and water tightness to function as one, integrated building layer. These properties can be used advantageously to replace conventional, multi-layer building systems that are constructively complex. This is called *part-count reduction*.

Another form of integral integration is the combination of primary and secondary structural components. The parapets and handrails of bridges are an example of this type of structural integration. In many of Robert Maillart's reinforced concrete arch bridges, he used the parapets as major beams that carried all of the moment induced stresses in the bridge. This

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[10] Jacob, p20-25.

[11] Research is being conducted in this area by my advisor, Thomas Keller, of the Composite Construction Laboratory (CCLab) at the Swiss Federal Institute of Technology Lausanne.

allowed Maillart to minimize the thickness of the arch.[12] (**Appendix A-06, p.A.275, Fig. 8**) The stiffening trusses of suspension bridges are probably the antecedents to these deck-stiffened arches. The first known use of the deck-stiffened arch was in the Risorgimento Bridge, designed by the Italian Hennebique licensee, Società Procheddu, in 1911 over the Tiber River in Rome.[13] (**Appendix A-06, p.A.274, Fig. 7**) Similarly, Jürg Conzett used the glue-laminated handrails of the Traversina Footbridge to stiffen the light and flexible superstructure.[14] (**Fig. 4.8**)

The integration of aesthetics in structural form is an important influence on the conception and development of structural form. The Swiss engineer Christian Menn ranks the importance of aesthetics in structural design fourth, after security, serviceability and cost. The subject of structural aesthetics has been variously examined.[15] Because of the complexity and, frankly, contentiousness of this issue, I will not go into more detail here. However, I will give two examples of what I consider excellent integration of structural form and aesthetics. Jean Prouvé, a French engineer, designed the window mullion shown in **Figure 4.10**. This form of the mullion expresses its duel purpose of supporting the glazed façade and transmitting wind load to the roof structure and the ground. The form itself is an expression of the extrusion process used to fabricate it, which is characteristic of aluminum. Pier Luigi Nervi's Risorgimento Bridge[16] in Verona, shown in **Figure 4.11**, expresses the varying moment stresses in the reinforced concrete bridge by varying the dimensions of both the cross section and longitudinal sections of the continuous beam. The twisting form of the flanges further

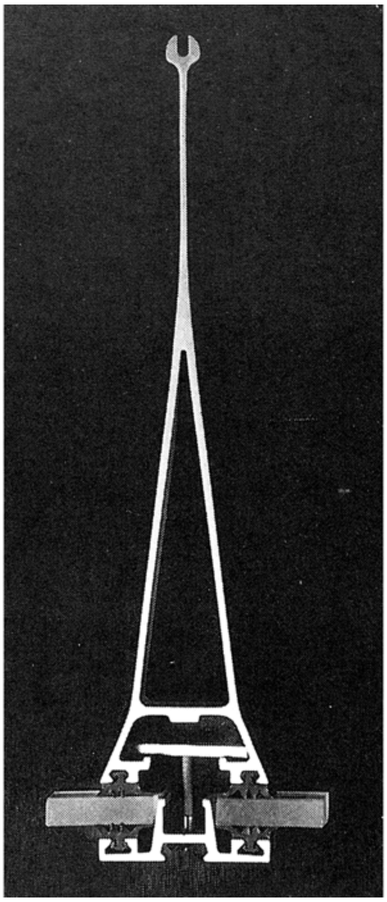
Fig. 4.10: Extruded aluminum window mullion. Jean Prouvé. (Coley)

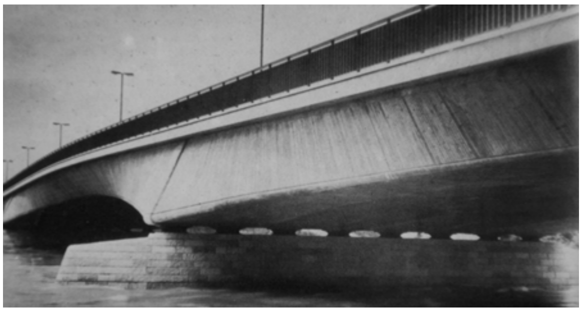
Fig. 4.11: Risorgimento Bridge, Verona, Italy. Pier Luigi Nervi, 1968. (Desideri et al.)

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[12] **Ref. Appendix A-06, p.A.274-A.275**. Christian Menn, another Swiss engineer, later reduced the thickness of the parapet beams too, realizing that Maillart's thin reinforced concrete arch had some capacity to carry moment.
[13] **Ref. Appendix A-06, p.A.274-275**.
[14] Gili.
[15] Ref. Nervi, Dieste, Billington, Peters, Sandaker, Collins, Siegal, Viollet le Duc.
[16] Desideri et al., p.159-163. Central span 62 m, each side span 34.5 m. Completed 1968.

Fig. 4.12: Systems design. (Haller)

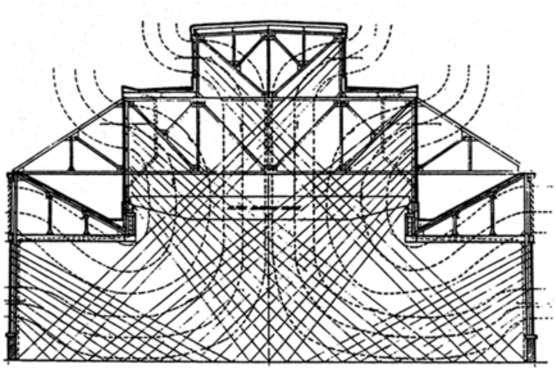

Fig. 4.13: Light and ventilation factory study. (Mislin)

expresses the plastic nature of concrete that is poured into a form. **Chapter 05** further addresses the topic of aesthetics and structural form.

The work of Fritz Haller, a Swiss architect, is an example of *complimentary integration*. Haller explored the relationship between structure and mechanical systems.[17] **Figure 4.12** shows one system he devised in which the structure and the mechanical systems were conceived of at the same time such that the mechanical systems fit within the depth of the steel structure, thus minimizing the thickness of the floors. Such a system also facilitates access and maintenance of the mechanical systems. The structure shown in **Figure 4.13** supports light and ventilation functions of the building. The saw-tooth roof form of factory buildings is similarly derived from these purposes.

4.2.7 Function Pattern Example

The annexed case study on the Britannia Bridge illustrates the influence Function Patterns can have on the development of structural form.[18] The emergence of rail transportation in the early 19th century created a new programmatic function that had not existed before. This new function resulted in new building forms and the advancement of building systems, among which were the development of long span roofs. Rail traffic also changed the design standards for bridges. Trains exerted higher loads than horse and carriage traffic, or even modern vehicular traffic. Trains are also more sensitive to deflections because of how they are linked and their overall length. This means that stiffness, in addition to strength, is a significant structural criterion for railroad bridge structures.

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[17] Haller.

[18] **Ref. Appendix A-03**. Robert Stephenson designed the Britannia Bridge in collaboration with the industrialist William Fairbairn and material scientist Eaton Hodgkinson. The account of its development is well documented in books by William Fairbairn (1849), Edwin Clark (1850), who was the contractor for the project, and G. Drysdale Dempsey (1850).

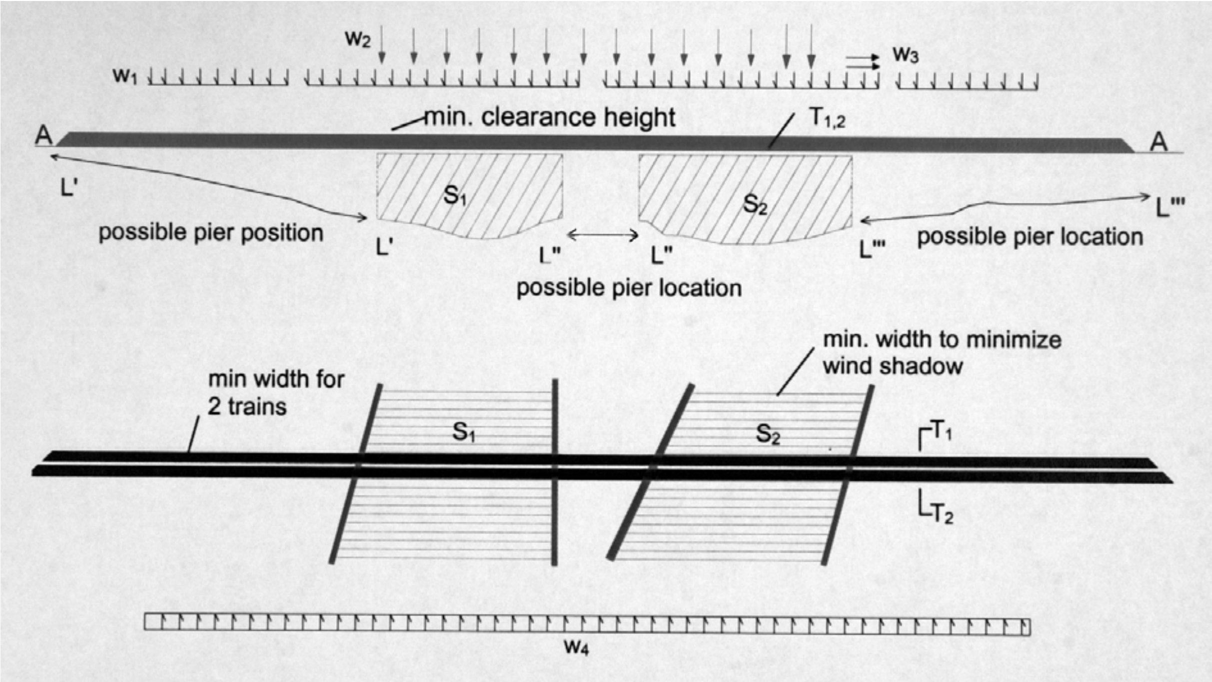

Fig. 4.14: Function Pattern for the Britannia Bridge spanning the Menaï Strait between England and Wales. Robert Stephenson, 1850. (Dooley)

The principal functional criteria governing the design of Britannia Bridge were:

- Traverse the Menaï Strait with two tracks for rail traffic.
- Build the bridge in the fastest time possible because every day it was not in service was lost income to the railroad.
- Do not interfere with shipping traffic as per decree of the Royal Navy.

A strait bounded by rocky shores with uneven slopes characterizes the site. (Appendix A-03, p.A. At the site chosen for the crossing, a small island is located in the middle of the strait. The gross span to be crossed is 561 m (1,841 ft) from the tops of each palisade.

Section 4.7 explores the influence of time requirements on economics in more depth. The economic influence is important here because it perhaps contributed to the pursuit of the ultimately realized tube beam even when initial testing produced discouraging results.

The requirements of the Royal Navy meant that the shipping lanes could not be obstructed during construction and that the completed bridge could not interfere with sailing vessels, either by not providing enough clearance or creating wind shadows that would adversely affect handling of the ships. The practical consequences of these restrictions made it impossible to erect a temporary structure upon which to build the bridge. The Royal Navy rejected an arch proposal because they thought that it would create wind shadows.[19]

Figure 4.14 illustrates the Function Pattern for this bridge. Line A-A fixes the level of the track. The shaded areas marked with a T denote the space that must be clear of obstruction for the train to pass. Shaded areas S^1 and S^2 denotes the space required by the Navy to be

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[19] **Ref. Appendix A-03, p.A.81-A.82**.

left clear of obstruction during and after construction so that the bridge does not interfere with shipping. Loading conditions are indicated as follows: W_1 is the dead load of the structure (the breaks denote where the piers were actually constructed); W_2 is the dynamic live load imposed by the train vertically (this is not to scale!); W_3 is the axial load imposed if the train makes an emergency stop while crossing the bridge, and W_4 is the wind induced lateral load. These loads are separated from the structure in the illustration for clarity. Load discharge points can be placed anywhere along lines L'-L', L''-L'', and L'''-L'''.

Robert Stephenson, the chief engineer, considered truss and suspension systems. Stephenson rejected using a truss because it was a relatively new system and there was no definitive method for calculating its strength and behavior. Squire Whipple, an American bridge builder, did publish a treatise on the subject in 1847. It was either unknown to the designers of Britannia Bridge or considered inadequate.[20] In any case, Stephenson was convinced that the truss would not be stiff enough; perhaps an opinion arrived at based on experience with timber trusses. Stephenson similarly rejected using a suspension bridge because he believed the system was too flexible to accommodate rail traffic.[21]

Having eliminated most structural options then available, Stephenson looked for novel solutions. He decided that the best solution was to reconsider using a suspension system but with a robust stiffening system made of iron plates instead of a truss. From this idea, Stephenson realized that he could analyze the resulting tubular form as a giant beam that a train could pass *through*.[22] After intensive research and development, the tube was sufficiently strong to stand on its own. Auxiliary chains, planned by Stephenson to be installed to provide the tube with extra support, were not needed. The tubular concept satisfied the restrictive functional restraints of the project.

When considering the Function Pattern and why Stephenson had considered a large beam earlier, we have to remember scale effects. The span was quite large and beam bridges built to that time did not begin to approach the spans of the Britannia Bridge.[23]

One functional aspect the designers of the Britannia Bridge failed to adequately consider was the fact that the engines exhausted a lot of smoke. Stephenson did not design the tubes with apertures for ventilation. Nevertheless, the Britannia Bridge tubes remained in continuous service until 1970, when a fire, set by some children playing under a protective wood roof that covered the tar-covered upper flange of the bridge, irreparably compromised the structural integrity of the wrought-iron bridge. The tubes were subsequently dismantled. Steel arches were put in their place because there was no longer a requirement for large sailing ships to clear the bridge. The masonry piers were preserved.

In the example of the Britannia Bridge, we see a Function Pattern that engineers had not confronted previously. This Function Pattern is the result of a historically new programmatic function, the railroad, in combination with a particular site condition and government imposed restrictions to keep the shipping channel free from obstruction. Historically new

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[20] Only 50 copies of Whipple's book are known, therefore the book was probably not available to Stephenson.

[21] **Ref. Appendix A-03, p.A.92 and A.79-A.81**.

[22] **Ref. Appendix A-03, pA.82-A.83.**

[23] For more about the development of iron beams, **ref. Appendix A-03, pA.93-A.105**. Experience and knowledge gained from the construction of the Britannia Bridge led to the development of the plate girder by William Fairbairn, who had already started research in this area before his involvement with the Britannia Bridge.

programmatic functions lead to new forms and material usage, as exemplified in the Britannia Bridge. Other examples include the relationships between the train stations and long-span roofs, rigid airships and spatial structures, and airplanes and monocoque construction. Either, new dimensional requirements as they relate to the scale problem, or new form requirements as they relate to new programmatic and structural functions characterize these new developments.

4.2.8 Function and the Development of Structural Form

Function influences the development of structural form through historically original Function Patterns and Function Integration. Function Patterns generally influence the development of System Form, while Function Integration influences System, Component, and Detail Form.

The general influence of new Function Patterns is to:

- Increase the amount of space that must be spanned or enclosed.
- Increase the loads that must be supported.
- Limit the space in which a structural system can be built to satisfy the Function.

Throughout history, new functions have increased the volume of space to be enclosed and spanned. The Greeks and Romans built increasingly large temples and civic buildings. During the nineteenth century, shipbuilders began to work under the protection of long-span roofs.[24] The navy, both military and mercantile, was the most important means of projecting power and creating wealth through trade. Railroads also necessitated the invention of new building types in the nineteenth century that led to even longer span roofs. The railroad networks in turn helped to improve the movement of goods and information, leading to a stronger economy. This new economy justified building longer span bridges subject to strength and stiffness constraints theretofore without precedent, because there was a desire to move goods and information even faster. The Britannia Bridge was one product of these new Function Patterns. Function Patterns do not directly translate into structural form; rather they define constraints that limit form and material selection. The spatial constraints of the Function Pattern can be modeled graphically. These graphical models help to define the space in which a system must occupy, which limits the number of possible design solutions.

The influence of Function Integration on the development of structural form is more quantifiable than for Function Patterns because the problem begins with existing forms. The objective of Function Integration is to combine these forms in order to reduce structural complexity and maximize material efficiency. The first aerodynamic envelopes of airplanes were non-structural. Efforts to minimize the weight of airplanes led to the development of stressed-skin, monocoque structures, which are simply the product of integrating the frame with the aerodynamic envelope. Similarly, Robert Maillart was one of the first engineers to develop a new structural system, the flat slab, by integrating unidirectional floor beams into the plane of the floor slab itself and placing the reinforcement in two directions. (**Appendix A-05, p.A.261, Fig. 39**) The result was an efficient, two-way spanning system that minimized material usage in floor construction.[25]

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[24] Sutherland, p107-126.

[25] **Ref. Appendix A-05, p.A.258-A.265**.

4.3 Material Properties

4.3.1 Types of Material Properties

Materials have both *intrinsic* and *attributive properties*. Intrinsic properties are a material's physical and chemical properties. Engineers separately classify intrinsic properties as being *structural* and *non-structural*. These properties, described in more detail below, relate to the *security* and *serviceability* of a structure. They can be considered constant because they describe the nature of a material as it is intended to be used in the structure and do not relate to the properties of the material before or during processing.

A material's attributive properties are: *cost; sustainability characteristics*; *processing properties*; *connectability;* and *constructive characteristics*. The following sections examine the latter three properties separately. **Section 4.4** addresses sustainability. **Section 4.7** addresses material cost. Attributive properties are not constant because of their interdisciplinary relationship to other technological domains such as mechanical engineering and its importance to processing technologies.[26]

4.3.2 Structural Properties and Structural Form

Summary of Properties and their Purpose

Structural Properties are: density; yield and ultimate strength in tension and compression; the elastic and shear modulus; fracture toughness; ductility; thermal coefficient of expansion; and creep characteristics.[27] These properties determine a material's suitability to specific structural applications. They must ensure the structural security and structural serviceability of a structure. To meet these requirements, engineers ensure a material has adequate strength, stiffness, and, if necessary, resistance to fatigue for a given application and load condition. A material's creep characteristics must also be considered to ensure the security and serviceability of a structure over time.

Density and Strength Properties

The relationship between *density* and the conception of structural form is surprisingly complex. Stone is considered a "heavy" material, yet its specific gravity is 2.7, the same as aluminum alloys, which are considered "light". The specific gravity of reinforced concrete is approximately the same and is also considered "heavy." Steel is considered "light" even though its specific gravity is 7.8! These perceptions of "heaviness" and "lightness" are

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[26] Vocabulary of *intrinsic* and *attributive* from Ashby[2], p10, Figure 1.7.

[27] *Density* = weight per unit volume of material; *Yield (or elastic) strength* is defined differently for different materials and has units of MPa or psi. For metals it is defined as the 0.2% offset yield strength, representing the stress at which the stress-strain curve for uni-axial tensile loading deviates by a strain of 0.2% from the linear-elastic line. For polymers, the elastic limit is the stress at which the uni-axial stress-strain curve becomes markedly non-linear, typically at a strain of 1%. For composites, the elastic limit is best defined by a set deviation from linear-elastic uni-axial behavior; *Ultimate strength* = the stress at which a material fails, either by rupture in tension or crushing in compression; *Fracture toughness* = the resistance of a material to the propagation of a crack; *Thermal coefficient of expansion* = thermal strain introduced into the material per degree Kelvin when heated. If the material is thermally isotropic, the volumetric expansion per degree is three times the thermal expansion coefficient. If it is anisotropic, two or more coefficients are required and the volumetric expansion is the sum of the principal thermal strains; *Ductility* = the permanent increase in length of a tensile specimen before fracture, expressed as a fraction of the original gauge length; *Creep* = the slow, continuous deformation of a material with time that makes the strain dependent not only on stress, but also time and temperature. (Definitions of material properties referenced from Ashby[1] and Ashby[2])

attributable to the visual association between structural form and the materials those forms are made from.

The visual difference between masonry and iron structures of the nineteenth century is stark. Ironbridge, the first all cast-iron bridge in the world when completed in 1779, is visually and materially light compared to the stone arches of the same period. (**Appendix A-02, p.A.41, Fig. 17; Appendix A-09, p.A.366, Fig. 22**) While Ironbridge does indeed weigh less than the stone bridge, the correlation between material weight and form cannot be substantiated. The stone bridge weighs more because more material is used to build it than with iron. This disparity is accounted for by stone's relatively low compressive strength, 125 MPa (18 ksi) for marble, compared to 655 MPa (95 ksi) for gray cast iron. Material weight and structural weight should not be confused. Therefore, weight has to be considered in the context of strength as well, but does the weight of a material actually influence the conception of structural form?

To complicate the argument, the weight of a stone arch is actually an advantage. The large self-weight of a stone arch, which is so much higher than any reasonable live load it will be subject to ensures that the arch will remain in compression. This is important because a stone voussoir arch has neither the mechanical nor the material capacity to resist tension. If tensile stresses in a masonry arch do develop, the arch will probably collapse. Stone's low tensile strength has nothing to do with this failure mechanism because the arch will fail by rotation of the voussoirs. If the material fails, it will fail by crushing at the point where a hinge forms between two voussoirs.

In the case of Ironbridge, its low structural weight was a disadvantage because it was not heavy enough to resist the movement of the embankments, as a stone arch may have.

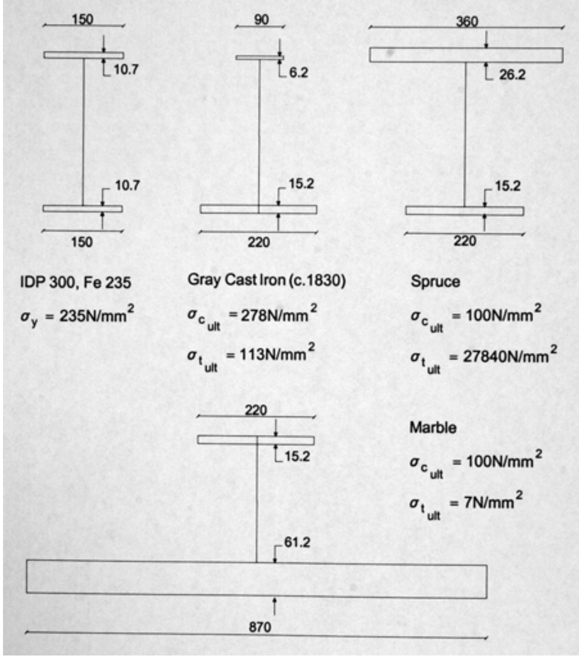

Fig. 4.15: Equivalent flange areas for beams made of different materials: Standard, mild steel I-section; gray cast iron c.1846; spruce; and marble. Beam depth and steel flange proportions kept constant for basis of comparison only. (Dooley)

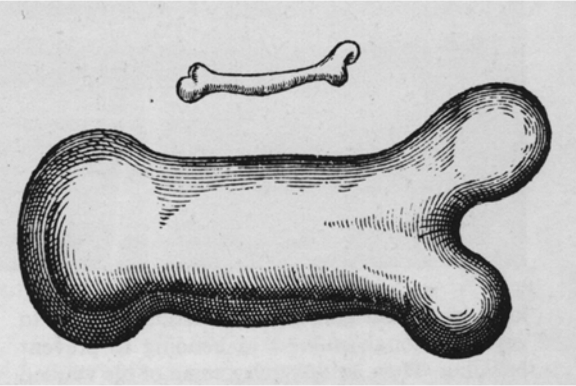

Fig. 4.16: Galileo's scale problem example: a human femur scaled three times its normal size. (Galilei)

The crown of Ironbridge moved upwards as a result. Thomas Telford addressed this problem when building the Buildwas Bridge. Telford did not try to increase weight. Instead, he designed the double-arch system described before in which he intended the arch with the lower rise to counter movement of the riverbank. Nonetheless, Ironbridge has not failed and one reasons is that it has a capacity to resist tension mechanically and materially.

As a general principle, low weight is not usually an overriding concern in the design of normal buildings and bridges. High weight is beneficial in the case of the stone arch. Low weight is a particular factor for the design of special structures such as portable or prefabricated structures used in offshore oil platforms or in space. Weight is a further factor in evaluating the global costs of using one material versus another with respect to construction process. A potential economic advantage of FRP is the fact that it can be erected in larger prefabricated pieces using smaller equipment than is the case for steel construction. However, material weight is best considered relative to other material properties such as strength and stiffness.

Strength properties limit the range of structural types to which a material can be applied. A material that is weak in tension and brittle, such as stone or cast iron, would not be suitable to a form-active structure subject to tension. However, such absolute rules are not generally discernable. One assumes today that stone is not a suitable material for a beam because if a crack develops it will propagate quickly through the brittle material, causing the beam to fail. The Greeks and Egyptians, nevertheless, used stone beams extensively. The existence of intact beams over two thousand years old in Egyptian and Greek ruins proves stone's suitability for the purpose. (**Appendix A-01, p.A.4, Fig. 4 and p.A.15, Fig. 15**) Therefore, while strength might be an important parameter in determining materially suitable structural form, it is not necessarily exclusive.

The principal influences of strength properties on form are to determine the proportions of structural cross-sections and to limit the scale of a structural system made of a particular material. If the cross-sections of beams made from several materials are considered, such as the examples shown in **Figure 4.15**, we can clearly see how material strength affects the *proportioning* of component level form. The example shows the equivalent flange sections of **I**-sections made of mild steel, gray cast iron, spruce wood and marble. A standard, steel **I**-section was chosen as the base of comparison. The beam depth was kept constant and the proportion of the steel flanges was used for the other materials for comparison. Similarly, a stone and reinforced concrete shell can have similar global forms, but the stone variant will be thicker in order to accommodate any point and asymmetrical loads through the thrust lines of the section. The steel of the reinforced concrete relieves this burden because of its capacity to transmit moment forces through the shell.

There is an interesting relationship between material density and strength. This relationship can be broken down into two categories: their effect of material density and strength on *scale,* and the effect of the strength-to-weight ratio on the conception of new structural forms.

Galileo was perhaps the first researcher to write of the *scale* problem in his *Dialogue Concerning Two New Sciences*. In this much-referenced example, Galileo explained the problem of scaling through the example of a human femur. (**Fig. 4.16**) Galileo showed that scaling up results in a proportional problem that would result in the person not being able to

Table 4.1: Material Limit Lengths (f_y kN/m^2 / γ kN/m^3). (Keller)

Material	Steel	Aluminum	Wood	Composites
Limit Length	~4-7 km	~10 km	~15-20 km	~20-200 km

Source: Keller

Table 4.2: Material property comparisons for some structural materials

		Tensile Strength		Strength for Weight		Young's Modulus		$\frac{E}{S.G}$	
Material	S.G.	psi	MPa	psi	MPa	psix10^6	MPa	psix10^6	MPa
GFRP Laminate (unidirectional)	1.85	150,000	1,000	81,000	550	5.0	35,000	2.7	19,000
GFRP Laminate (woven fabric)	1.85	75,000	500	40,000	280	2.5	17,000	1.35	9,000
Carbon Fibers (Unidirectional)	2.2	300,000	2,000	136,000	910	60.0	410,000	27.0	190,000
Mild Steel	7.8	60,000	400	7,000	50	30.0	210,000	3.85	27,000
High Tensile Steel	7.8	300,000	2,000	38,500	260	30.0	210,000	3.85	27,000
Gray Cast Iron (c.1842)	7.2	16,000	110	2,000	15	10.0	68,000	1.4	9,000
Duraluminum	2.7	57,000	390	21,000	140	10.5	73,000	3.9	25,000
Wood, parallel (Spruce)	0.4	15,000	100	37,500	250	1.7	12,000	4.3	30,000
Marble	2.7	1,000	7	370	3	8.7	60,000	3.2	22,000

Sources: Gordon[2]; Cotterell and Kamminga; Dooley

function as he did.[28] A different material would have to be used to achieve similar proportions. His defines his argument by the square-cube law, whereby a linearly scaled structure increases its cross sectional area to the square and its volume increases cubically. Therefore, the dead load of a structure increases on an order of magnitude larger than does the cross-sectional area that must resist any applied stress. At some point, a structure will fail under its own weight. We can use this benchmark to compare the relative strength-to-weight advantages of materials. **Table 4.1** compares the length at which different construction materials will fail under their own dead weight. To compare compressive values we can compare columns of different materials, discounting buckling phenomena. The effect of scale is that a different material or structural system needs to be used when the limits of a material's strength have been reached.

There are two significant periods in history where the relationships between strength and density have manifested themselves in profound ways. The first was in the 19th century, with the transition from massive stone construction to light iron construction. Iron has a much higher strength to weight ratio than stone. The second is the current increase of FRP use in construction. The strength-to-weight ratio of FRP is generally superior to steel. Both of these examples share two common denominators: lower gross weight of the structures made from these materials compared to contemporary structures made of conventional materials; and the need to develop structural forms that provide adequate stiffness. One of Robert

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[28] Galilei, p126-132.

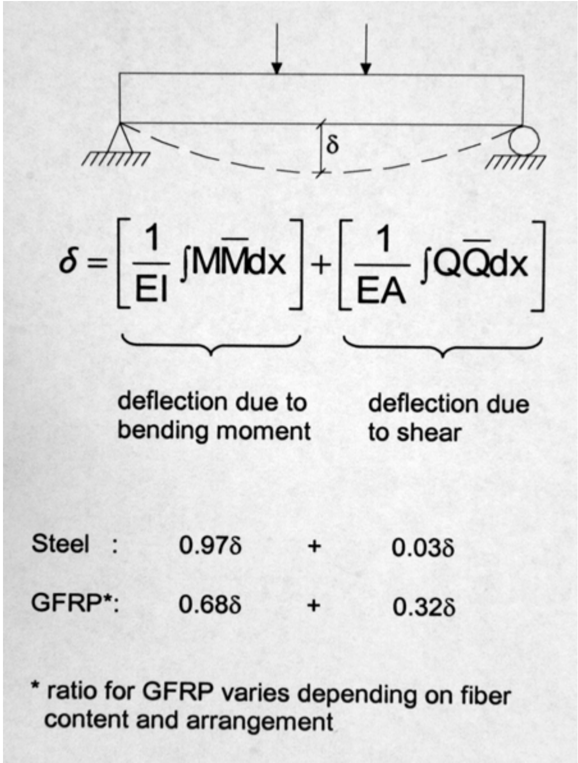

Fig. 4.17: Relative contribution of bending and shear to deflection for steel and GFRP. (Dooley, after Schollmayer)

Stephenson's challenges in designing the Britannia Bridge was ensuring adequate stiffness. Stephenson ultimately derived his solution from the stiffening trusses developed for suspension bridge construction.[29] Suspension bridges were subject to vibration forces induced by the wind and persons walking in lock-step. These forces were of little concern when bridges were made of massive stone arches. The imposed load on these arches was relatively small compared to the weight of the arch. The imposed load is more important relative to the weight of the structure in suspension bridges.

For FRP today, the proportion of imposed load to structure self-weight is even higher. Further steps are necessary ensure adequate stiffness in FRP structures and stability. One FRP suspension bridge had to have concrete ballast poured into its FRP sandwich-panel deck because wind induced uplift forces were too high for the light bridge deck.[30] An alternative solution to this problem would be to use a counter cable system.

Elastic and Shear Modulus: Stiffness

The *elastic* and *shear modulus* affect the *stiffness* of a material. The stiffness of a material such as wood or GFRP can be a controlling factor in design. The depth of the structure is dependent on deflection criteria and not strength. The contribution of the elastic and shear modulus to stiffness differs from one material to another. The shear modulus is not a significant factor for isotropic materials with an elastic modulus over 70 MPa (10 ksi). (**Table 4.2**) Steel, concrete, stone, aluminum, and most stones all have an elastic modulus over 70 MPa. Wood and GFRP have lower elastic modulus. Though CFRP has an elastic modulus of about 100 MPa, its shear modulus is only 3 to 4 MPa. Therefore, shear can account for 20-30% of deflection for CFRP structures. Special consideration has to be given to anisotropic materials to ensure adequate stiffness. Deflection criteria usually control the forms of such structures, meaning that the material's strength may not be fully exploited. **Figure 4.17** shows the relative influence of the elastic and shear modulus for mild steel and GFRP. Such a relationship indicates that the design approach for GFRP must differ from steel in some way. How it does and should differ is the topic of current research.[31]

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[29] **Ref. Appendix A-03, p.A79-A.81**.

[30] Firth and Cooper. [info. on concrete fill related to Th. Keller by designers at a conference.]

[31] Prof. Thomas Keller, of the Composite Construction Laboratory at the EPFL, is currently examining such questions concerning FRP materials.

Stiffness is not an inherent property of a material because it depends not only on the material's elastic and shear modulus, but also on the geometry of the structural component. This fact is demonstrated by supporting a flat piece of paper between two books. The paper will either fall or have a high deflection. It will not support much load. If the paper is folded lengthwise like an accordion and again supported by the two books, it is readily observed that the paper deflects less and can support a higher load. (**Fig. 4.18**) This is a folded-plate structure. Doubly curved structural forms derive even more stiffness from their geometric properties. Therefore, we see that the form of a structure, as it relates to stiffness, is not uniquely a function of material properties alone.

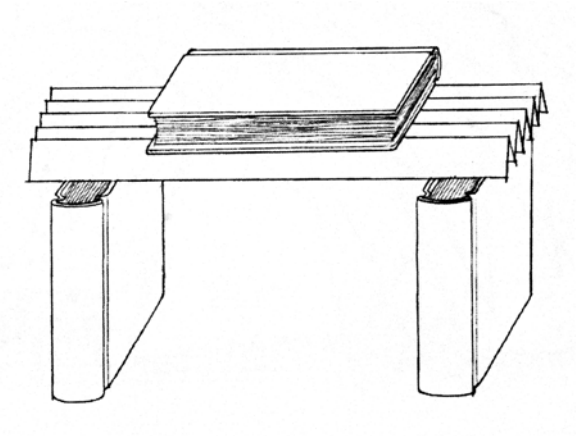

Fig. 4.18: Experiment showing effect of geometry on structural stiffness and strength. (Salvadori)

Ductility and Fracture Toughness: Fatigue Strength and Failure Behavior

Ductility measures a material's ability to deform before failing. This quality is important in engineering materials to avoid sudden failure of a structure. This property is also useful when processing materials. Cast iron cannot be rolled because of its brittleness, while steel can be drawn into very fine wire. When steel is so worked, it strain hardens, which reduces the ductility but increases its tensile strength.

Fig. 4.19: Fatigue failure of the US Liberty Ship *Joseph-Augustin Chevalier*, World War II. Liberty ships were made from prefabricated ship sections. Some of these ships were put together in as little as four days. (armed-guard.com)

Structures that give forewarning before total failure are desirable. Ductile materials, such as steel, noticeably deform when overloaded. The objective is to have large deflections before failure so that occupants can be secured and, if possible, remedial action taken before total failure. When wood is subject to bending, it will fail by buckling of the fibers in compression. Before failure, the wood redistributes the load taken by these fibers to the fibers in tension.[32] Wood will also have a high deflection before the structure fails. Normal concrete fails suddenly by crushing.

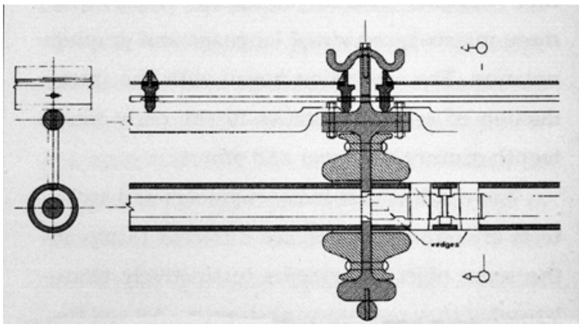

Fig. 4.20: Structural detail of the Palm House at Kew Gardens, London. Richard Turner, 1848.

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[32] Gordon^2, p140.

Therefore, reinforced concrete is made to fail ductility by designing the steel reinforcement to yield before the concrete crushes.

Steel's ductility allows structures to be designed using plastic methods. That is, the design method accounts for plastic failure of the structure, economizing material. This cannot be done for a material like aluminum that is not as ductile. Aluminum's yield stress is too close to its ultimate stress, making it susceptible to rupture without adequate warning.

Fracture toughness measures a material's ability to resist crack propagation. For brittle materials, this is a defined value because cracks propagate rapidly in these materials. In ductile materials, a plastic zone develops at the crack tip, which introduces new features into the way cracks propagate. This necessitates more complex characterization, but the important fact here is that a ductile material will usually slow crack propagation. The failure of many cast-iron railroad bridges in England during the first half of the nineteenth century illustrates the importance of fracture toughness.[33]

Ductility and fracture toughness relate to a structure's *fatigue resistance*. Fatigue resistance is important for any structure subject to dynamic loads, such as bridges. Fatigue cracks usually start at a detail, such as a connection or an opening. An important tool in preventing fatigue cracks from forming is the geometric form of a detail. Invariably, rounded corners are preferable to sharp ones. This is one function of the fillet of a welded connection. Famous examples of fatigue failures come from aviation and shipbuilding. The De Havilland Comet, one of the first successful commercial jet airliners, was withdrawn from service because of several flights in which the tail of the plane broke off. During World War II, the United States built a series of ships called Liberty Ships, which were fabricated very quickly. Numerous ships of this type split through the hull in transit.[34] (**Fig. 4.19**) In both cases, cracks had formed at the corner of an opening in the structure. The size of these structures and their catastrophic failure illustrates the importance of Detail Form to the security of structures.

Coefficient of Thermal Expansion

A material's *thermal coefficient of expansion* is important to analysis, composite materials, and function integration. For analysis, the thermal coefficient of expansion is used to calculate the stresses induced by expansion when a structure is heated by the sun or fire, or contraction in extreme cold regions. For structures exposed to sun, System and Component form can be adapted to minimize the effects of differential expansion when one part of the structure is exposed to the sun and another part is in shade. This effect can be limited in bridges by cantilevering the deck so that the superstructure is always shaded.

The coefficients of thermal expansion for the constituent materials of a composite material must be close enough that internal stresses due to differential expansion do not damage the material. The similar coefficients for steel and concrete make reinforced concrete possible. Similarly, different expansion coefficients need to be accommodated when connecting two materials together, particularly in function integration applications such as fixing glass to a metal structure. These problems affect Detail Form. One example of this is the connection between the wrought-iron structure and glazing of the Palm House at Kew Gardens in England. Richard Turner, an Irish engineer, constructed the Palm House in 1848. (**Fig. 4.20**)

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[33] **Ref. Appendix A-03, p.A.102-A.104**.
[34] Petroski, p115-116 and p166-180.

In this structure, Turner had to accommodate the contradictory requirements of building a stiff structure that could also support the glazing. The glazing would crack if rigidly connected to the metal superstructure because their different coefficients of thermal expansion. Turner resolved the problem by separating the different problems into distinct layers and putting them together as a "component subset in a construction system."[35]

Creep

Creep is particularly problematic for concrete and polymer based structures, but does not significantly influence form. Prestressed concrete structures are subject to two types of creep: creep of the concrete and relaxation of the prestressing tendons. These cause losses of the prestressing that have to be accounted for in design so that enough prestressing is introduced to be effective after the losses have occurred. Excessive prestress losses can compromise the security of the structure if the concrete can be subjected to unacceptably high tensile stress.

4.3.3 Non-Structural Properties and Form

Non-structural properties are related to a material's surface and environmental interaction properties, its thermal and electric conductivity, and acoustic characteristics. These properties primarily affect material choice. Some properties have been addressed in **Section 4.2.3** pertaining to the subject of function integration. A material's surface properties and its resistance to oxidation, corrosion, and wear are important serviceability issues that affect appearance and durability, but do not generally affect form.[36]

The *thermal conductivity* of a material will affect Detail Form, particularly in buildings. Thermally conductive materials create thermal bridges that are deleterious to controlling the climate in the building and causes energy inefficiency. Structural members can be thermally isolated while maintaining their structural integrity. An example is the aluminum window mullion designed by Jean Prouvé, shown in **Figure 4.10**. Insulating rubber gaskets are used between extruded aluminum components that clamp the glass. Several bolts connect the external aluminum component to the main mullion.

4.3.4 Role of Material Science

Material science is concerned with the acquisition of knowledge about material properties. Material science relates physical properties to the microstructure of the materials. The importance of material science lies in how the knowledge it produces can be used to best exploit a material's unique combination of properties.

Poor understanding of a material's properties leads to wasteful and inefficient use of a material. In 1822, Thomas Tredgold published one of the first significant treatises on the

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[35] Peters[1], p218-220.

[36] The influence of language on design parameters is worth noting here, though a more in-depth study is outside the scope of this thesis. Just because stainless steel is called "stainless" does not prevent it from corroding. In 1988, the suspended ceiling of a swimming pool in Uster, Switzerland, collapsed, killing twelve persons. The ceiling was a reinforced concrete plate suspended from the roof by 10 mm thick, chrome-nickel V2A steel bars. The space between the roof and the ceiling was used for ventilation. Subsequent forensic analysis of the failed roof revealed that the chrome nickel steel bars were damaged by chlorine vapor. The engineers and architects lacked experience in the design of suspended ceilings and accepted chrome-nickel steel a "stainless" steel even though stress corrosion had been known for more twenty years before the accident happened. [Ortega, p4-5.]

strength of cast iron. Tredgold based his results on a poorly conceived test method. Tredgold determined the strength of cast iron by measuring the deflection of cast-iron beams under their own dead load. Erroneously, Tredgold assumed that cast iron is equally capable of carrying tension and compression. As a result, Tredgold proposed that the appropriate form of cast-iron beam should have flanges of equal area.[37] (**Appendix A-03, p.A.100, Fig. 30(a)**)

Today we benefit from over two hundred years of development in material science. There are limits, however, to the knowledge material science can provide. Material scientists learn about materials by using relatively small test samples. Their work cannot predict such things as local-torsional buckling in steel I-sections or explain the vibration characteristics of stayed cables in conditions of light wind and rain.[38] These types of behavioral characteristics can only be learned through experience and large scale testing versus small sample testing in a material science laboratory.

4.3.5 Material Architecture

Homogeneous and Composite Materials

A material's *internal architecture*, or Element Form, is critical to its engineering characteristics. Structural materials can be classified under two categories relating to their internal architecture: *homogeneous materials* and *composite materials*.

The internal microstructure of *homogeneous materials* is controlled during fabrication through a phase change. Stone is produced through various geologic mechanisms in the earth's crust. The founding process and controlled cooling rates determine the microstructure of metals. The properties of metals can be adjusted by working the metal cold and heat-treating.

Composite materials, such as engineered lumber, reinforced concrete and fiber reinforced polymers, are interesting because the designer can control the internal architecture of the material to achieve an optimal flow of stress, which should result in material efficiency. Unlike metals, whose structural properties are defined by their homogenous microstructure, the structural behavior of composite materials is determined by how the internal elements are arranged by the designer. The reinforcing bars in concrete can be shaped such that the material acts linearly, as in a beam, or in multiple directions, as in a flat slab. The orientation and geometric structure of the fibers in FRP is important. In an FRP I-section, the fibers can be orientated longitudinally in the flanges for axial stress and in different directions in the webs to efficiently transmit shear stress. The most efficient arrangement of fibers for axial loads is if the fibers are straight and parallel to the line of force.

Composite materials should not be confused with composite structures such as steel-concrete composites or cast iron underspanned with wrought iron. (**Appendix A.03, p.A.104 and A.105, Figs. 34 and 35**) Possible exceptions can be made for the wrought iron reinforced cast-iron beam shown in **Appendix A.03, p.A.103, Fig. 33**, or wrought-iron beams and plates made from bar piles heat welded and rolled. (**Appendix A.03, p.A.110, Figs. 39**

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[37] Tredgold, p55-56. **Ref. Appendix A-03, p.A.101-102**.

[38] The cables of the Fred Hartman Bridge, a cable-stayed bridge in Texas, USA, deflect of up to two meters under such conditions. Ref. Tuchman.

and 41) In these examples, two grades of iron are homogenously formed to create a new material with its own properties. The grades of iron are beneficially placed to exploit the strength properties of each.

Isotropic and Anisotropic Materials

Materials can also be classified by the sense, or directionality, of their strength properties. Materials that can resist force differently when measured in different axes, such as wood or hemp, are called *anisotropic*. *Isotropic* materials such as steel or plain concrete can resist force equally in all directions.

Composite materials cannot be easily classified by the above protocol. The complexity arises from the disparity between the classifications of a composite material's constituent parts and how the composite material actually behaves in application. Reinforced concrete is comprised of two isotropic materials, concrete and steel, but because the steel is in bar form, the reinforced concrete has anisotropic properties. FRP is made from an isotropic matrix material, but the fibers can be either isotropic, like glass, or anisotropic, like carbon and aramid. In either case, the material will behave anisotropically because the fibers are linear elements. Though it is theoretically possible to arrange the fibers in such a way to make an isotropic material, it is practically impossible with existing processing technologies. Furthermore, such an arrangement would have one-sixth the strength of fibers oriented in parallel, so there would be little advantage in doing so.[39] The critical issue to consider about composite materials is that the designer can control the structural properties of composite materials by specifying the arrangement of the constituent materials.

The usefulness of *isotropic* and *anisotropic* classifications towards the development of material-adapted forms is not self-evident. There is contradictory evidence about the 'nature' of a material using this classification and the forms in which the material is conventionally used.

Plain timber, an anisotropic material, can principally carry load in one direction, parallel with the fibers. The anisotropic classification is consistent with the linear form wood is typically used in. Conversely, isotropic metals, capable of carrying stress in all directions, are also used in linear forms such as beams, struts and cables.

Steel would appear to be ideal for plate and shell structures, and it is indeed used as such in shipbuilding and some types of bridge structures. Steel plates are rarely used in building construction except as corrugated panels used for cladding and composite steel-concrete floor construction. Steel plates are not utilized more because the material is difficult to form when it is in thick sections, it is prohibitively heavy, prefabrication requirements limit the component size, and the material is simply too expensive to make solid steel floors with. The problem of using steel in materially appropriate ways illustrates the difference between Ideal Form and Implemented Form. It must be concluded that any definition of material-adapted form has to address this discrepancy.

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[39] Gordon^2, p189.

4.3.6 Composite Materials and Controlling Material Architecture

Engineers increasingly have more control over the internal architecture and composition of materials. As this trend develops, chemical properties and how they can be manipulated to achieve certain structural characteristics may become more important to the design of structures. Engineers already specify concrete mix design, where the ratio of water to cement is a critical factor in determining the strength of the cured concrete. It is conceivable that the development of nanotechnology will some day make it possible to fabricate structures molecule by molecule.

The use of composite materials already blurs the line between material science and structural engineering. Early examples of composite materials whose structural behavior is designed into the internal details of the materials being used are: the iron reinforced stone structure of the Eglise de Sainte-Geneviève in Paris; Marc Brunel’s iron-reinforced brick cantilever; and heat-welded, wrought-iron beams that fused different grades of metal into the same structural section. (**Appendix A-03: p.A.95, Fig. 20; p.A.112, Fig 45; and p.A.110, Figs. 39 and 41**)

Composite materials are comprised of two or more materials, whereby one or more of the materials complements another material’s deficiency. Concrete has a high compressive strength and can be formed into large, monolithic structural components; but normal concrete has little capacity to resist tensile forces. Therefore, steel or glass fiber reinforcement is used to carry tensile forces. The reinforcement also helps control cracking and shrinkage.

Fiber reinforced polymer materials, contrary to their name, are characterized by an inverse relationship between their constituent materials than exists in reinforced concrete. In FRP, it is the fibers, being the dominant structural material, that are reinforced by the matrix material. The fibers cannot resist compressive forces alone because they are too thin and flexible. This flexibility is not entirely negative. This quality enables the fabrication of complex structural forms. The fibers cannot hold these forms without some aid. Unlike reinforced concrete, where steel bars or glass fibers reinforce the concrete matrix, the matrix of FRP laterally braces the fibers to prevent buckling. The matrix also provides the means to restrain and maintain the fibers in complex forms. The matrix is a medium that transfers forces from one fiber to another. Connecting the fibers individually is impractical.

The internal architecture of composite materials is reactive to Component Form and not a form generator. This means that the constituent materials of a composite material are best exploited when the stress distribution is known. Therefore, System and Component level form-finding has to proceed before design of the internal material architecture can proceed.

4.4 Processing Technologies

4.4.1 Processing and Workability

Material Processing Technologies are all of those processes, both mechanical and chemical, that are necessary to work raw materials into finished structural products. Whether a material is poured and cast like concrete, rolled like steel and aluminum, or manipulated in any way is partially dependent upon the material’s properties. Material properties specific to

Table 4.3: Approximate energies required to produce various materials

Material	η = energy to manufacture (Joules x 10^9 per ton)	Oil equivalent (tons)
Steel (mild)	60	1.50
Titanium	800	20.00
Aluminum	250	6.00
Glass	24	0.60
Brick	6	0.15
Concrete	4	0.10
CFRP	4,000	100.00
GFRP*	16	0.40
Wood (spruce)	1	0.025
Polyethylene	45	1.10

Note from source: "All these values are very rough and no doubt controversial; but [Gordon thinks] they are in the right region. The value given for carbon-fibre composites is admittedly a guess; but it is a guess founded upon many years of experience in developing similar fibres." (Gordon[1], p319 (1978); * Fiberline (c.2000); Ashby & Jones[1])

processing are: ductility, hardness, yield and ultimate strengths, and toughness. The temperature and physical state of a material when it is worked is important. These properties characterize the *workability*, of material. Material workability can be separately broken down into *attributive properties* that include: ease of manufacture, fabrication, joining, and finishing. The workability of a material determines what processing methods can be used to create form.

4.4.2 Material Properties and Processing Technologies

How a material is worked into a form is a critical link between material properties and form in general. An important aspect to consider is the role phase changes – when materials change from liquids to solids – have on structural conception. The production of steel, FRP, engineered wood and concrete all require phase changes of one constituent material. Metals are extracted or recycled in liquid form at very high temperatures. The controlled rate of cooling of a metal will affect its microstructure and, thereby, the metals physical properties. Different cooling rates can result in a metal that is more or less ductile, stronger or weaker, etc. Engineered woods are composed of wood fibers held together by an adhesive. Adhesives used in plywood manufacture need to be heated and cured under pressure. Similarly, FRP materials are composed of fibers and a polymer matrix. Some matrix materials need to be heat cured while others, like polyester, do not. Concrete is prepared as a viscous mix which is placed in molds that are left in place until the cement cures. This can be done at ambient temperatures.

The phase change temperature is an important parameter determining how a structure can be built using one material or another. Section 4.6 addresses this issue in more detail. It suffices to say here that the net effect of the phase change temperature is to limit the size of structural components that can be fabricated depending on whether they must be fabricated off-site, at a central processing facility, or can be processed *in situ*.

The structural properties of composite materials are determined by processing. The shaping and placement of steel reinforcement in concrete is rather straightforward. As Robert Maillart demonstrated with his flat slab reinforcement design, three-dimensional structural behavior can be achieved with a simple two-dimensional arrangement of reinforcing bars. Maillart showed that the concrete would transfer forces as a plate with the bars crossed perpendicular to each other, obviating the need to orientate the steel in the direction of multiple stress lines like C.A.P. Turner.[40] (**Appendix A-05, p.A.255, Fig. 34 and p.A.261, Fig. 39**) This quality gives great flexibility to the reinforced concrete design because material efficiency is balanced with constructive simplicity. The relative stiffness of the reinforcing bars makes it cumbersome to try to optimize the form of the reinforcement. On the contrary, the fibers used to reinforce FRP materials are thin and flexible, making it more practical to optimize their configuration. The relative cost of the fibers to steel reinforcement further justifies optimization.

4.4.3 Sustainability

The issue of material sustainability is included here because it involves the processes used to reclaim a material, and the costs involved in that process. Sustainability is a subject of expanding importance in construction and will have ramifications on design in the future. Sustainability issues primarily influence material choice however and have little influence at present on structural form. Material choice is based on sustainability criteria that include material supply, processing costs and recyclability.

Material supply is concerned with the source and relative abundance of materials. Wood is sustainable because it can be continually replenished primarily from the free energy of the sun. Oil-based polymers have a more finite supply, especially because their reyclability is questionable. However, polymers derived from plant stock may prove to be a sustainable source for these materials. Steel and aluminum can be fully recycled, though their ore supply is finite. However, these materials will be plentiful for some time into the future through a balanced use of new and recycled material.

Processing costs can be determined in a holistic way to include the energy to process the material from its naturally occurring sources plus the energy content of the source material itself. **Table 4.3** gives the energy content and the equivalent quantity of oil to produce that energy for a number of engineering materials. Other factors such as more subjective criteria concerning environmental impact can also be considered.[41]

Recycling is part of sustainable development and this can be achieved in two ways. The first is to have closed-loop recyclability, such as when a soda can is recycled and made into a soda can again. Metals are generally closed-loop recyclable, meaning that a portion of all new structures made of metals can be made from recycled material, reducing the amount of raw material that needs to be taken from the earth. The second mode of recycling is so-called ‘down-cycling’. Down-cycling is when a material cannot be reprocessed to perform its first-use function. Such materials will often be broken down and used as additives or fillers in other materials. Non-recyclable materials must be disposed of, by either burning or

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[40] **Ref. Appendix A-05**.
[41] Berge.

dumping. The costs of disposal facilities can also be incorporated into a material cost analysis.

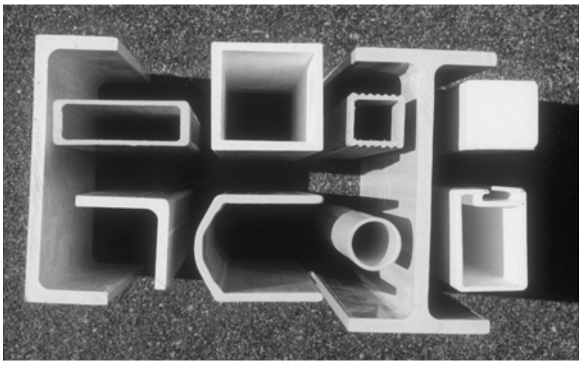

Fig. 4.21: Pultruded FRP sections. (CCLab)

4.4.4 Processing Technologies and Structural Form

Ideal, Constructible and Implemented Forms

Processing Technologies do not influence Ideal Form but do largely define Constructible Form[42]. The comparative costs of different Processing Technologies also weigh on the choice of Implemented Form. Processing Technologies influenced the cast-iron beam forms of both Thomas Tredgold and Eaton Hodgkinson. (**Appendix A-03, p.100, Figure 30**) In Tredgold's case, he determined that the thickness of the flanges and webs should be equal to avoid deleterious stress concentrations caused by uneven cooling when casting the beam. The web of Hodgkinson's 'ideal' cast-iron beam section was actually thicker than the thickness Hodgkinson calculated because it was not possible at the time to reliably cast a web that was thinner. When Hodgkinson's beam form was used in practice, his tapered web was changed to one with parallel sides that reduced processing complexity and cost.[43] Today, pultruded FRP components with sections typical of steel components are used today in lieu of forms that are more complex. This is similarly because of processing complexity and cost. (**Fig. 4.21**) Pultruded FRP components are made by pulling fibers through a resin bath and then through a die where the resin cures. (**Fig. 4.22**) Shapes that are more complex require complex moulds and lay-up procedures.

Processing, Form, and Construction Process and Method

The following overview demonstrates how structural form is affected by the way in which a material is handled.

Metals typically require high temperatures and large machinery to create forms. Even cold forming requires large machines. Cold rolled metals also need to be heat treated after the material has been elongated a certain percentage, which strain hardens the material and makes it more brittle. Therefore, metals are necessarily fabricated at centralized locations and transported in prefabricated Components.

Ductile metals are worked into forms by rolling, hammering, bending, and other dynamic action. Brittle materials such as cast iron and concrete are cast. Ironically, the form of ductile metals has resulted in more limited structural forms because their properties are amenable to linear processing methods, such as rolling and extrusion, producing linear, prismatic Component Forms. In contrast, cast components exhibit greater formal complexity and material efficiency. (**Figs. 4.23**)

FRP materials require controlled conditions to ensure the quality of the material and current technology makes it difficult to fabricate forms on site. Therefore, FRP materials are mainly pre-fabricated as Components at centralized facilities and then assembled on site. Like

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[42] These terms are introduced in **Chapter 03**.

[43] **Ref. Appendix A-03, p.A.101**.

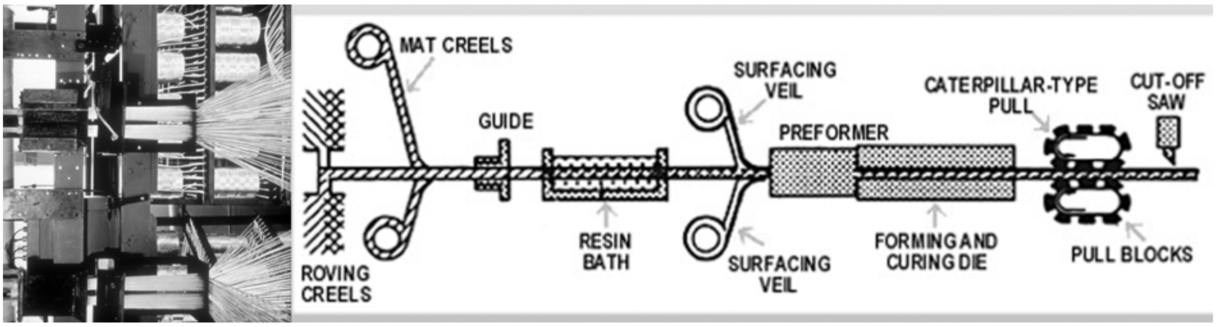

Fig. 4.22: Pultrusion machine. Linear production process: fibers and fiber textiles are pulled through a die where the matrix material is injected and cured. (CCLab)

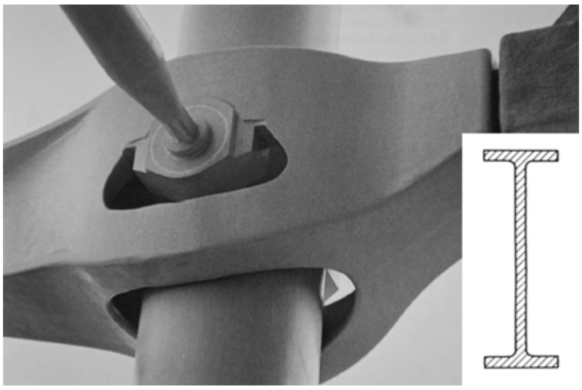

Fig. 4.23: Cast steel geberette at connection, Pompidou Centre, Paris, compared to a standard, rolled **I**-beam. (Dunster; Mainstone)

Fig. 4.24: Example of the hand lay-up method of producing complex FRP component. In this case the mold was formed with earth, however better quality can be attained in factory conditions.

ductile metals, FRP for construction applications is most economical when formed into linear structural forms produced using the pultrusion process. (**Fig. 4.21**) Complex FRP structures were formed manually until recently; making such forms prohibitively expensive for construction. (**Fig. 4.24**) New methods of fabrication developed for the marine, aeronautic and automotive industries may make complex FRP structural forms affordable for construction applications.

Concrete, in contrast, is a cast material that can be worked at ambient temperature. This makes it possible to form large, monolithic structures *in situ*. (**Fig. 4.25**) A material like steel or aluminum must be prefabricated into transportable elements and then connected on site. (**Fig. 4.26**)

System, Component and Detail Form

If the components can be made, then constructibility is governed by connection technology and construction methods. Therefore, processing technologies do not affect system form.

Processing Technologies do have a significant effect on Component Form. Peter McCleary analyzed the difference between construction details of the Ste.-Geneviève Library and the French National Library designed by French architect Henri Labrouste.[44] (**Figs. 4.27 and 4.28**) These libraries have similar structural

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[44] McCleary.

systems comprised of iron-framed vaults. The difference is that the vaults of Ste.-Geneviève Library, built 1845-1850, are cast iron, and those of the National Library, built 1862-1868, are wrought iron. **Figures 4.28 and 4.29** show the differences between the two materials when used in nearly identical System Forms. In Ste.-Geneviève, the trussed arch is cast in parts and assembled on site with pinned joints. The floral-patterned web is characteristic of the plastic, complex forms that can be made by casting. Such forms cannot be rolled. In the National Library, the wrought-iron arches are pre-fabricated as single units. Each unit is built up by riveting rolled bar and angle sections together. The constructive details become decorative components themselves. The rivet patterns create a new vocabulary of architectural ornament. The curvilinear floral form of the web in the cast-iron arch is now a simple lattice arrangement of flat bars, revealing a more direct correlation between structural form, processing technology, and architectural aesthetic.

Detail Form

The processing attributes of a material can be useful for identifying Function Integration opportunities. For example, extruded aluminum can be formed into very complex forms. Importantly, closed sections with multiple cells can be produced, something that is not possible with rolled steel products. **Figure 4.30** shows the possibility of simplifying construction details using extruded aluminum in lieu of steel. The steel member is composed of four separate components that are either welded or bolted together. Such a detail increases structural weight and constructive complexity in the field. The equivalent aluminum section is one integral component, reducing weight and constructive complexity.

Fig. 4.25: Free-form, reinforced concrete thin shell. Sicli Factory, Geneva. Heinz Isler, 1969. (Chilton)

Fig. 4.26: Monocoque aluminum dome, diamter = 100 m. Meeting Hall, Longview, Texas. R.G. LeTourneau Co., 1953. (Peter)

Fig. 4.27: Ste-Geneviève Library, Paris. General view. Henri Labrouste, 1850. (Dubbini)

Fig. 4.28: French National Library, Paris. Henri Labrouste, 1868. (Dubbini)

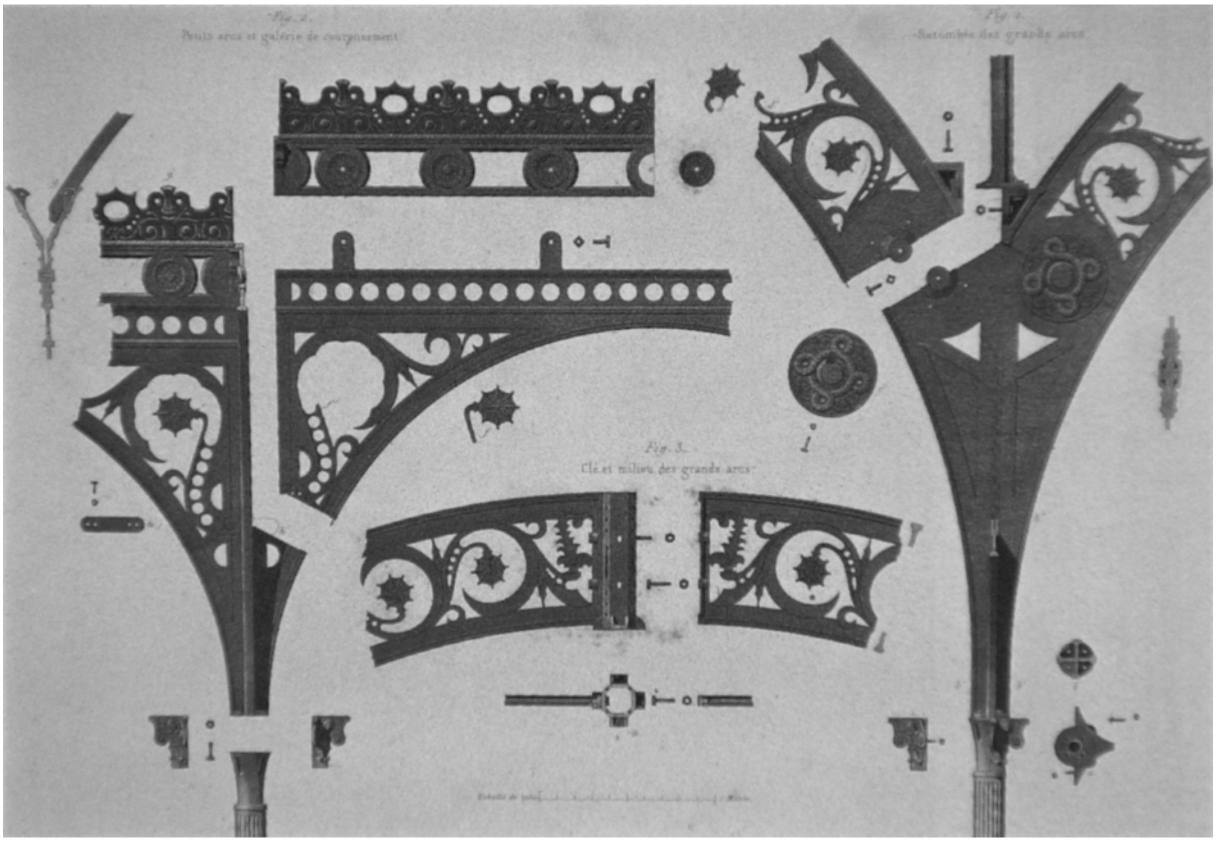

Fig. 4.29: Ste-Geneviève Library, Paris. Detail of cast-iron arch. Henri Labrouste, 1850. (Dubbini)

4.4.5 Processing Technologies and Material Development

Processing Technologies are particularly important to Material Development. The reviews of the evolution of iron and aluminum in **Appendix A-09** illustrate how there is a direct correlation between new processes and the emergence of new structural forms. Successful improvements of material technology usually result in what I consider a critical component of material development: increased productivity, better quality, and decreased cost. This relationship is tied to the *accessibility* of a material. Material accessibility can be defined as the threshold of economic and market supply factors that make it sensible to invest in the use of a material for a particular application.

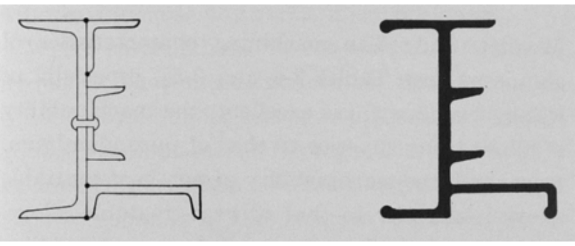

Fig. 4.30: Function integration possibilities of extruded aluminum versus steel. (Peter)

When aluminum was first manufactured, its cost made it a precious metal. It was therefore used in applications such as jewelry and sculpture.[45] As the cost decreased, aluminum was used in applications that are more diverse. Ferdinand von Zeppelin probably would have had to exclude aluminum as a material from which to build his airship if the cost of aluminum had not been as low as it was when he began his search.[46] Because Zeppelin *did* use aluminum, new structural forms were developed.

The spatial trusses and spatial structure created for the Zeppelin airframe led to further developments in lightweight, spatial structures in the aviation industry through the work of one-time Zeppelin employee Claude Dornier. Other manufacturers also developed lightweight structural systems and forms, but Zeppelin's work should be treated as an influential antecedent to all other developments that followed. Through interdisciplinary technology transfer, spatial structures were developed for building construction, evidenced by the work of American engineer Buckminster Fuller.

Luftschiffbau Zeppelin's development of thin-walled structural components is surely under-appreciated in the field of structural history, perhaps erroneously attributed to the development of heavier-than-air aircraft. Zeppelin engineers Ludwig Dürr and Dornier refined the fabrication of thin-walled structural components to a high state of material efficiency. (**Appendix A-04, p.A.208-209, Figs. 37 and 38**) This knowledge was transferred to airplane construction and later to building systems. (**Appendix A-09, p.A.379, Figs. 32 and 33**)

The Zeppelin history is just one illustration of the importance of material availability and cost to the development of materials. Others are the stagnant period of development in France during the Napoleonic Empire because iron prices were exorbitantly high,[47] or the early development of the aluminum industry that was also hampered by material cost. Therefore, the developer of materials ought to be interested in ensuring that these conditions are continually improved. The historical evidence in **Appendix A-09** substantiates my contention that *increased diversity of material application is achieved by increasing material production and quality, and decreasing cost*. Like the concurrent development of the **I**-section in shipbuilding, railroad construction, building and bridge construction, and academia, inter-disciplinary technology transfer is instrumental to the development of both structural materials and forms.[48]

4.5 Connection Technology

Connections link two or more structural components together. They can be either monolithic, such as welded and adhesively bonded connections, or mechanical, such as bolted and riveted connections. Structural function and material properties determine Connection design. Their first function is to ensure structural security and serviceability. Connections influence the overall structural behavior of the System and can be classified as hinged, rigid, or semi-rigid. How the connections behave is critical to how stresses will be distributed throughout a structure.

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[45] **Ref. Appendix A-04, p.A.158-A.165, and Appendix A-09, p.A.373-375**.
[46] **Ref. Appendix A-09, p.A.375, and Appendix A-10, p.A.402, Fig. 2**.
[47] Steiner, p29 and 32.
[48] **Ref. Appendix A-03, p.A.93-A.105**.

Connections are normally designed stronger than the Components being connected. However, some connections are designed to fail in such a way that overall structural security is ensured. Such connections might be used in structures subject to seismic forces. Controlling the failure mechanism of a structure is an important part of connection design. Detail Form is especially critical to minimizing the formation of fatigue cracks in structures subject to dynamic loading. Sharp corners in connections subject to dynamic loading should be avoided because stress concentrations will be higher than if the corner is rounded.

Connections are a specialized area of design in normal engineering practice. Engineers often delegate the design of connections for steel structures to detailers who specialize in this work. Connection design for other materials will rarely be done before the structural system and component forms have been determined. Additionally, the forms of connections are arguably more integrally linked to a material's specific properties than either Component or System Form. Material properties are related to Processing Technologies, which in turn limit Constructible Form. The stress concentrations that are particular to connections make the conception of structural form different than for System and Component Form. Except for steel, it is often necessary to use a secondary material to make mechanical connections. This in turn raises questions of material suitability, or choice, rather than development. As such, I will not further expand on the subject of connections and Detail Form in this thesis.

4.6 Construction Process

4.6.1 "Process" Engineers

Construction Process constitutes the means by which structural systems are assembled. This process has to account for issues such as construction loads, site conditions, labor, equipment and material markets, and the project delivery method used to organize the design and construction of the project. The historical record shows that the most respected engineers have made the construction process an important element in their work, though not all have integrated that process directly into structural form. Gustave Eiffel combined the most current structural analytical methods with refined construction processes to design functional, economic, and beautiful structures. His bid to build the Douro Bridge in Portugal was 30% lower than the next lowest bid.[49] (**Fig. 4.31**) Turner and Maillart's flat slabs simplified the construction of reinforced concrete floors, eliminating the more complex beam-slab floor characteristic of the Hennebique System.[50] Similarly, Jean Muller's development of external prestressing in the 1970s was motivated by a desire to make prestressed-concrete box girder construction simpler, more economic, and easier to inspect for corrosion.[51] This section shows how construction issues can influence the Function Pattern, and how aspects of the Construction Process can be integrated into the conceptual phase of form-finding.

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[49] Loyrette, p61.

[50] **Ref. Appendix A-05**.

[51] **Ref. Appendix A-06, p.A.313-A.314**.

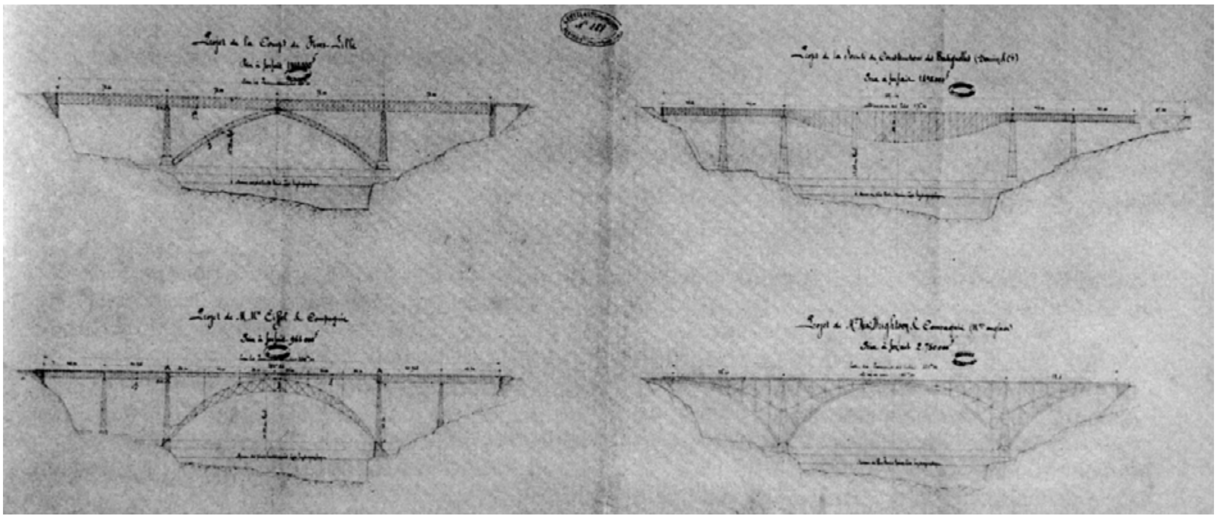

Fig. 4.31: Douro Bridge competition proposals. Eiffel's design (lower-left) was bid for 30% cheaper than the next lowest bid. (Loyrette)

4.6.2 Constructibility and Material Properties

The constructibility of a structure is linked to the material's physical properties and processing attributes. The workability of a material is obviously important to the execution of a constructed work. Material properties determine whether a structural form will be prefabricated or fabricated on site. On-site fabrication gives certain advantages that pre-fabrication cannot, such as the freedom to make structural components larger than the transportable sizes pre-fabricated components must respect.

Material properties also influence the skill levels and number of workers necessary to build a structure. Concrete is a relatively forgiving material and requires relatively low skilled labor, but *in situ* construction requires many workers to prepare formwork, place the concrete, and remove the formwork. Steel work requires fewer workers, but higher skill levels.

The weight of a material is a significant factor in determining the size and type of equipment necessary on a job site. A benefit of FRP materials is their low weight, which requires smaller equipment than a comparable steel structure for instance. The economic savings of using smaller equipment can help offset the relatively higher material cost of FRP. Weight, particularly lightness, is an important factor in the conception of complex or irregular forms. Aluminum is light, ductile, and easy to drill. It can be rolled into thin plates. These plates can be connected together to make monocoque structures such as in the media center at the Lord's Cricket Ground.[52] (**Appendix A-09, p.A.382, Fig. 41**) Such a structure would be much more complex to construct with steel because its weight makes it more difficult to manipulate the shell segments around the site and into position. Steel would necessitate the use of heavier equipment. The importance of material properties to constructibility issues lies in how the process of construction is influenced by the particular properties of a material and how this process in turn influences the conception of structural form.

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[52] This is actually semi-monocoque structure, but the principle is the same.

Fig. 4.32: Reinforced brick vault with Gaussian form. Citricos Caputto Packing Plant, Salto, Uruguay. Eladio Dieste, 1972. (Torrecillas)

4.6.3 Construction and Function Pattern

Constraints imposed by the construction process can be incorporated into the Function Pattern. The conception of a structure can include parameters about the maximum transportable size and weight. A major limiting factor in the design of Conzett's Traversina Footbridge, shown in **Figure 4.8**, was that the superstructure had to be transported by a helicopter with a maximum lifting capacity of 4.3 metric tons. This criterion determined the need for a light structural system.[53] Similarly, the main structural spine of the International Space Station is an aluminum truss designed to be transported in segments on US space shuttles. (**Appendix A-04, p.A.161, Fig. 13**) The truss had to meet strict size and weight requirements. Its hexagonal form is partly due to the shape of the cargo bay of the shuttle. Constructive restraints related to working in space led the designers to design a simple four-bolt connection system between the segments.[54]

4.6.4 Local Labor and Materials Market

Local labor and materials market conditions can have important ramifications on structural design. The most frequent consequence is on material choice. The Petronas Towers in Kuala Lumpur were constructed of reinforced concrete because there was an established concrete industry in Malaysia, an island nation. Imported steel costs too much. The concrete industry was modernized and workforce was trained to construct the buildings.[55]

The seating bowl of Mile High Stadium, in Denver, Colorado was constructed with steel plate instead of concrete. There was not a sufficient supply of concrete in the region because of a strong construction market. The choice of steel had the side benefit of preserving the stadium's reputation for being one of the loudest stadiums in American football because of the sonorousness of the steel as thousands of excited fans stomp their feet on it.[56] This is an example of complementary function integration.

Two other examples demonstrate how local labor and materials markets can influence the conception of structural form. The first is the work of Uruguayan engineer Eladio Dieste. Dieste adapted the local clay brick building culture of Uruguay to the construction of thin shell structures. The Catalan vaults of Spain influenced Dieste. Dieste developed construction methods and equipment to construct reinforced brick shells. These methods influenced the way he created new shell forms.[57] He is perhaps best known for creating Gaussian vault form shown in **Figure 4.32**.

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[53] SIA article, author's conversation with the design engineer, Jürg Conzett.
[54] Fortner.
[55] Robinson, p63-65.
[56] Brown, p60-65.
[57] Dieste.

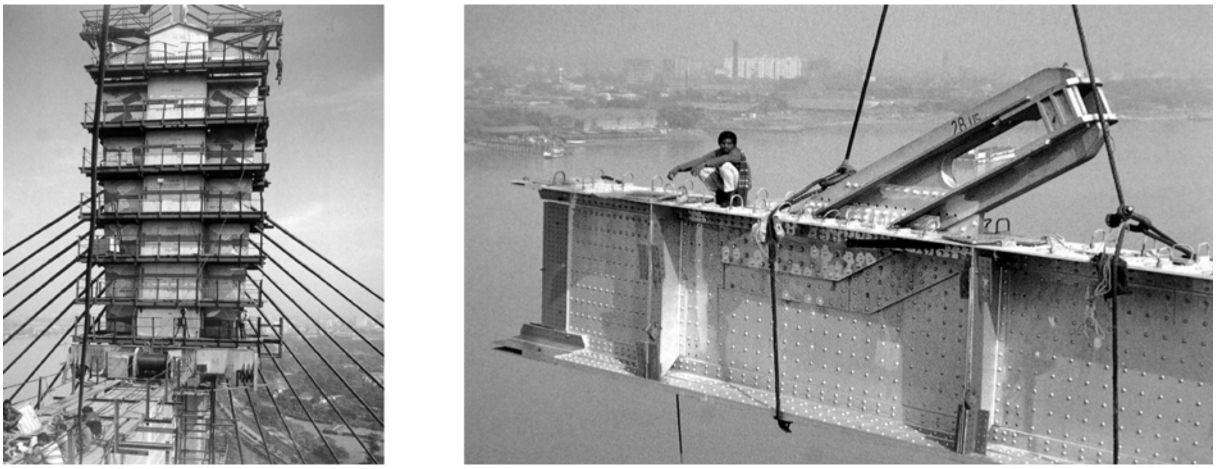

Fig. 4.33: Calcutta bridge, Schlaich. “Flower pot” type pylon achchorage design. Normally tendons are prestressed at deck level. It was decided to prestress the tendons on the pylon to ensure quality control and to facilitate inspection. The steel was riveted together by local labor. (Holgate)

A cable-stayed bridge designed by German engineer Jörg Schlaich for the city of Calcutta, India is another example of the influence of local material and labor markets. The local government required that Schlaich design the bridge in steel and use local labor to construct it. The limits of the local steel industry and construction workforce inspired Schlaich to develop structural forms and details that are reminiscent of the nineteenth century for a twentieth century structural type. The impact of these conditions is most apparent in Component and Detail level forms, especially in the cable anchorages, and the use of riveted connections and built-up components.[58] (**Fig. 4.33**)

4.6.5 Project Delivery Methods

Project Delivery Methods can change dynamics of design. Design-Bid-Build (DBB) is the most conventional project delivery method. Using DBB, the designer makes the full design and then bids the work to a contractor. DBB does not affect structural form because the design is fully developed before construction begins. The Design-Build (DB) project delivery method is different. Using this method, construction and design proceed at the same time; meaning construction begins before the final design is done.

The construction of the Britannia Bridge in the mid-nineteenth century is one of the first DB case studies.[59] The Britannia Bridge was constructed under severe time pressure because the railroad wanted to begin service as soon as possible. Robert Stephenson started constructing the piers before the final design of the superstructure, a novel tubular beam, had been determined. Stephenson ordered the towers built higher than the level of the beams so that auxiliary suspension chains could be installed if the tubular beam was not sufficiently strong. The distinctive towers, which look superfluous, are the product of a construction methodology. (**Appendix A-03, p.A.139, Fig. 73**) Their cost was justified by the time that would have been saved if the chains had to be installed.[60]

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[58] Holgate, p156-169.

[59] **Ref. Appendix A-03**.

[60] This argument was first made by Tom F. Peters (Peters[1], p178) quoted in **Appendix A-03, p.A.145**.

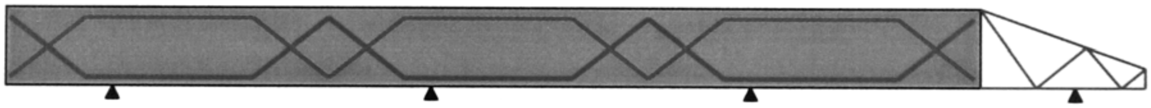

Fig. 4.34: Orientation of prestressing tendons in a launched prestressed concrete box girder bridge. (Vogel)

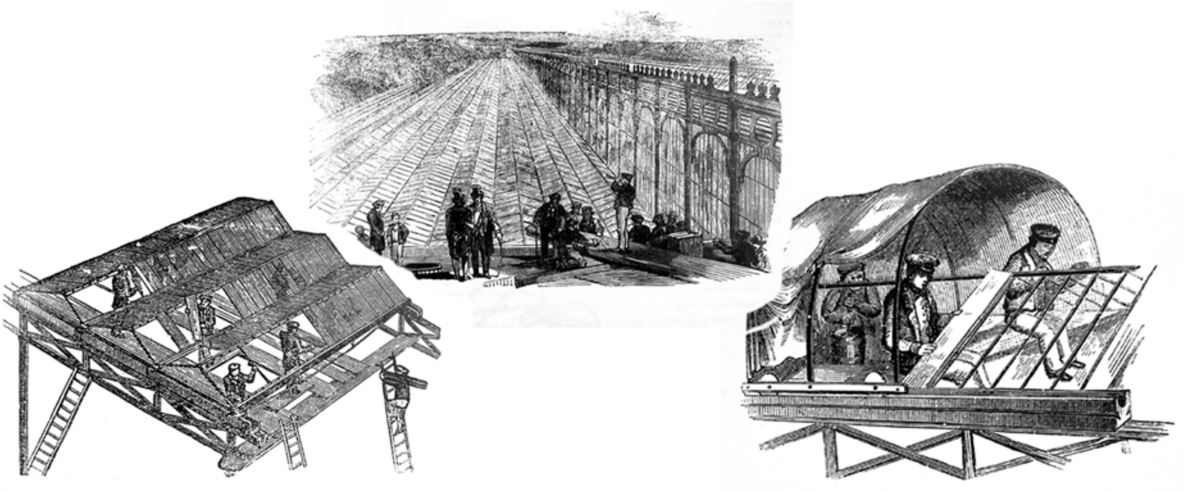

Fig. 4.35: Placement of glazing on Crystal Palace, London. (left) Method lacks organization. (right) Industrialized method. (Peters[1])

4.6.6 Construction Loads and Structural Form

Construction loads can influence the form of a structure. Robert Mark, a historian of building technology, explains that medieval builders probably adopted quadripartite vaulting in the vaults of High Gothic churches because the longitudinal horizontal thrust of these vaults was far lower (approximately half) than that of the sexpartite vault. This makes construction loads easier to manage.[61]

Whether a prestressed concrete box-girder has parallel flanges or variable depth is in part due to the construction method adopted for a particular bridge. The depth of the bridge can be variable if the bridge is erected using a gantry, fixed formwork, or the cantilever method. However, if the bridge is launched, then the bridge will have to have parallel flanges so that there is a continuous surface for the bridge to pass over the piers and to account for widely varying stress reversals in the beam as it is first cantilevered and then supported by the next pier. This method of construction requires that tendons be installed in two senses, as shown in **Figure 4.34**.[62]

4.6.7 Construction Process as an Element of Design

Tom F. Peters demonstrates in his book, *Building the Nineteenth Century*, that the building process influences technological thinking, and thereby the design process. Mechanization and industrialization during the nineteenth century resulted in the production of modular

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[61] Mark, p117, note 16.
[62] **Ref. Appendix A-06, p.A.305**.

building systems that reflected more rational organizational structures within the design and construction fields. James Strike shows in his book, *Construction into Design*, that this industrialization of the building process became even more prevalent after the Second World War, when modular building systems satisfied the need to speedily reconstruct and keep pace with the growing world economy.

The design of the Crystal Palace (1851) was governed, in part, by the speed with which a structure of its size could be built within a limited timeframe.[63] However, there was a disjunction between the industrialized processing of the building components and the construction process. Only when a delay was caused by the glazing process did the builder, Charles Fox, industrialize the construction process too. He used the gutters of the building as tracks on which a dolly could be shuttled, thus creating an assembly line. (**Fig. 4.35**) While Fox did not think of this aspect during design, contemporary designers can learn a lesson from this example and integrate construction functions into conceptual thinking of structure. Designers or developers can use this knowledge to examine where the state-of-the-art lay today, and examine how to better develop the use of materials through function integration.

4.7 Economics

4.7.1 Scope

The scope of economic issues related to the development of structural forms and materials is too broad to discuss in detail in this thesis. This section briefly outlines: the influence of economics on Implemented Form; the possible role of economics in form finding; and the general role economics plays in material development.

4.7.2 Economics and the Implemented Form

Economic criteria generally determine what forms are implemented. Chapter 03 related how Robert Stephenson chose to use rectangular cells instead of round cells for the flanges of the Britannia Bridge's tubular beam. He made this choice for reasons of constructibility and maintenance. The choice to use the rectangular sections reduced the cost of the bridge because its design simplified construction and provided better insurance against problems of corrosion. Additionally, there was no time to further develop the forms of the tubes because the company building the bridge had to open the railway line as quickly as possible to recoup its investment. In a letter from July 1946, Robert Stephenson explained his reasoning for using the less efficient form to Eaton Hodgkinson, who Stephenson hired as a consultant to develop the form of the tubular section. Stephenson wrote,

> In my position as engineer of the Holyhead Railway Company, and upon whom the responsibility of the Conway Bridge being completed in time for opening that portion of the line [rests], you must perceive the difficulty I labour under. The Directors are pledged to the shareholders to have this portion of the line open by a certain period, and I am bound (even at the risk of having not arrived at the very best mode of distributing the material of the tube) to proceed; for what the

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[63] **Ref. Appendix A-05, p.A.252-A.254**. Peters[1], p226-254 and 350.

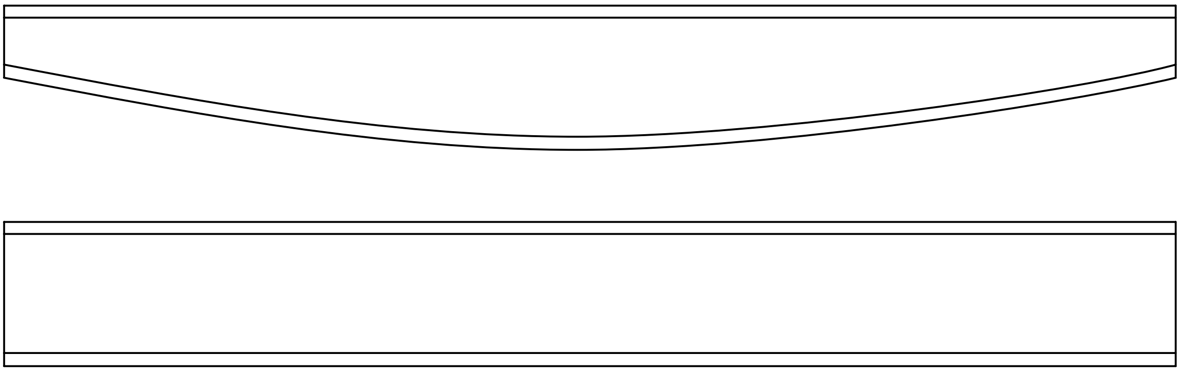

Fig. 4.36: Optimal Longitudinal Section vs. Standard Longitudinal Section of Steel **I**-Beam. (Dooley)

> consequence of delay, in a commercial point of view, after upwards of a million of money has been spent in finishing the works, not simply the interest, but the loss of income and these together, you will at once see, must become a very serious consideration both to the directors and shareholders.[64]

The standard steel **I**-beam provides a more general example of the role of economics in implemented form. The **I** -beam is generally considered an efficient Structural Component. Though the cross section is efficient, the longitudinal section is not because its parallel flanges do not optimally address moment distribution in the beam. Optimally, the beam would vary in depth along its length, being deepest at mid-span. (**Figs. 4.36**) While such a section is Constructible, it requires more energy, and therefore cost, to produce. A parallel-flanged **I** -beam is rolled directly from the furnace. A beam of variable depth can be fabricated by cutting off the bottom flange and a portion of the web and then welding another plate to form a new bottom flange. This is not economical for most applications. An exceptional example is the design of Embankment Place in London. Embankment Place replaced an older building and had to respect a maximum height requirement imposed by zoning regulations. The client wanted to build one more floor than what had existed before within the height limit of the old building. Using function integrated design, the engineers, Arups Ltd., specified tapered beams and used the voids under the beam to route the buildings mechanical and utility services.[65] (**Fig. 4.37**) In this example, the economic benefit of having an additional floor offset the additional cost of the structure.

Developers can use economic analyses to identify technological processes and other factors that make a form unduly expensive. With this information, resources can be focused to overcoming the economic limitations to making better Implemented Forms. Such a study may lead the developer to improving processing technologies or construction methods.

4.7.3 Form Finding and Economy

Economics cannot be translated directly into form, however it can constitute an important constraint in the Function Pattern. Structures with minimum mass or cost – not necessarily

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[64] Fairbairn[1], p88. **Also ref. Appendix A-03**.
[65] Dunster, p54-55.

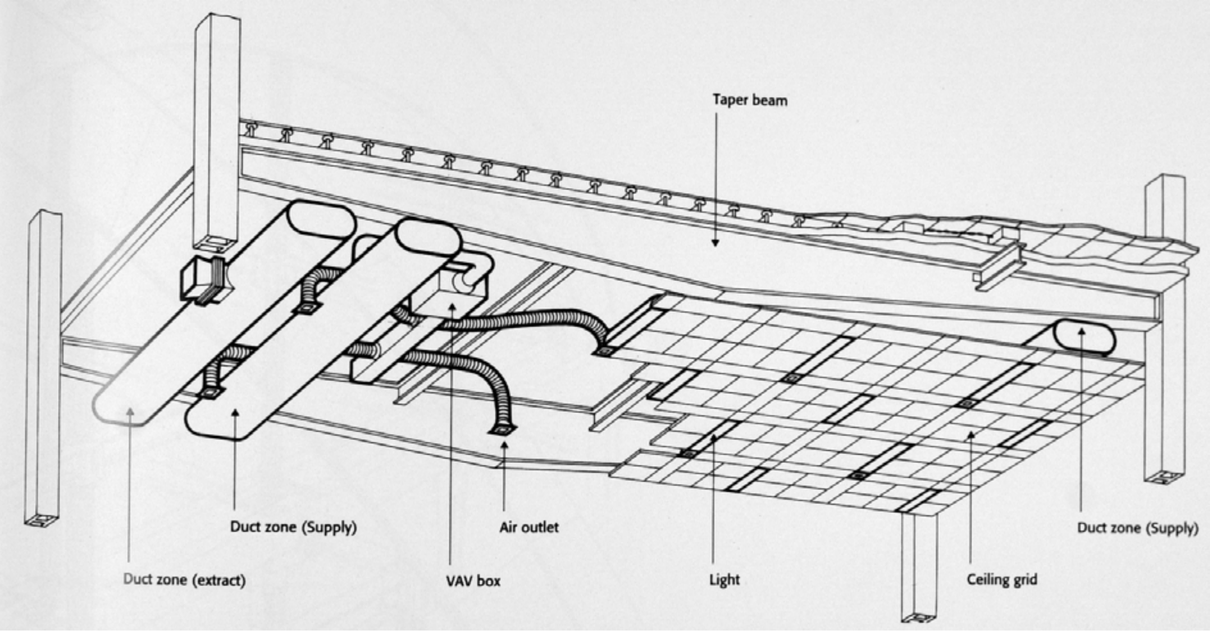

Fig. 4.37: Complementary function integration between steel structural system and building services. Emabankment Place, London. Ove Arup & Partners, engineers. (Dunster)

the same thing – are obvious examples. Such criteria can be applied equally to any form type for a given Load Pattern. Swiss engineer Heinz Isler approached the design of thin-shell reinforced-concrete structures seeking to minimize material usage.[66] Similarly, efforts to reduce the dead load of the webs of prestressed concrete box girders led to the development of external prestressing and trussed, open web forms. (**Appendix A-06, p.A.316, Fig. 72**) It should be noted that the trussed web introduces construction complexity and maintenance issues that offset any economy gained by using less concrete.[67]

4.7.4 Economics and Material Development

Section 4.4 discussed the importance of processing technologies to reducing the cost of structural components made from particular materials. A number of examples showed how reduced cost and increased production led to materials being used in a greater diversity of applications. Increased material use creates an environment conducive to the development of structural forms. This cost relationship can be expanded to include all economic issues contributing to the cost of using a material.

The costs associated with construction process and connection technologies can both be addressed technologically using a value engineering approach like French chemist Saint-Claire Deville did when developing the aluminum industry.[68] Certain parameters will lie outside of the developer's normal area of expertise. The developer can collaborate with others in related industries to help bring down those costs. Eladio Dieste adapted Uruguay's local brick building culture to the construction of efficient, long-span, reinforced-brick shell structures.

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[66] Chilton, p22.
[67] Muttoni, Aurelio. Lecture from the EPFL course *Conception du Ponts en Béton*, 2001.
[68] **Ref. Appendix A-04, p.A.159**.

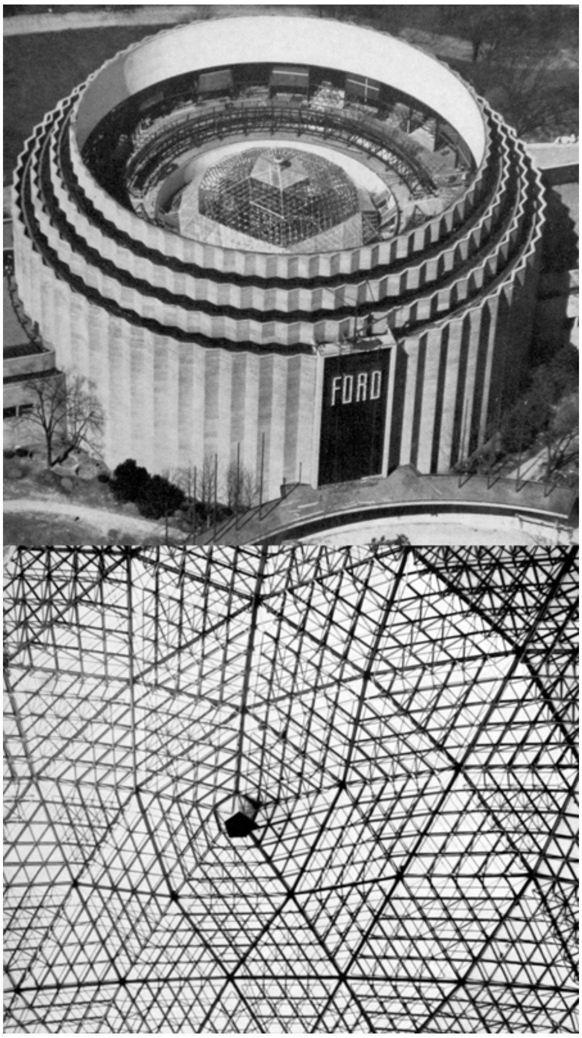

Fig. 4.38: Geodesic dome of the Ford Motor Company's headquarters, Dearborn Michigan. Diameter = 31 m, weight = 8.5 tons. Buckminster Fuller, 1953. (Peter)

For materials like aluminum and FRP that are more expensive than steel, concrete or timber, it is important to consider costs in a more holistic way than just material costs. This is generally referred to as *life-cycle cost* analysis. When experimental FRP building systems were being developed in the 1950s and 60s, the cost was prohibitive because of material costs and labor costs. Most FRP structures had to be formed with manual labor. Today, pultruded FRP Components are more affordable, but they still cost more than conventional structural materials. (**Table 6.2**) However, the lightness of these materials can be used to reduce construction costs. Their durability properties can be exploited to reduce maintenance costs, and their finish properties can be used to eliminate the need for secondary surface finishes, reducing constructive complexity and cost. Buckminster Fuller designed the aluminum geodesic dome of the Ford Motor Company Headquarters in Dearborn, Michigan, to be built by a low skilled labor force by creating a simple structural system that is comprised of aluminum tubes all the same length connected by simple, single-bolt connections. Unskilled laborers built the 31 m diameter dome in 30 days.[69] (**Fig. 4.38**)

Other aspects of economics require the developer to be a good businessperson, politically astute, a communicator and a salesman. Eiffel was an astute businessman, as was the successful concrete pioneer François Hennebique. Such skills are important when trying to introduce a new material or new structural forms to the construction market. If a new material or system is initially more expensive than conventional alternatives, it is imperative that the volume of constructed projects increases in order to realize economies of scale. Once a segment of the construction industry trains and equips to work with a material, then costs should reduce further through experience-related improvements. Precedent and experience best overcome the innate conservatism of the construction industry. To achieve that end, the developer of materials needs to convince government and the private sector that a new material or new structural system is a good investment. Only when clients begin to actually build projects using these new materials or systems can the economic restraints be addressed seriously.

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[69] Peter.

4.8 Socio-Political Factors

4.8.1 Scope

Socio-political factors comprise a broad body of political, sociological, and cultural influences. Like Economics, which are related, the subject of Socio-Political influences on the development of structural materials and form is too broad to address in detail in this thesis. This section reviews four aspects of Socio-Political factors related to the development of structural materials and forms. Three aspects are: the socio-political influence on Function Patterns; material choice; and the development of structural materials. The fourth aspect is patents.

4.8.2 Socio-Political Influence on the Function Pattern

Socio-political factors influence the Function Pattern actively through direct input from government and public bodies, or passively through general cultural and institutionalized rules and methods of design.

Governments affect the Function Pattern through regulations, environmental policies, etc. Environmental regulations are increasingly influential in defining Function Patterns. The North Halawa Viaduct of the H-3 Highway in Hawaii was designed specifically to minimize damage to the protected wilderness area that it traversed. In this instance, environmental concerns caused the contractor to use a form traveler method of construction such that once the piers were built, all other work was done from bridge level and not on the ground.[70] (**Fig. 4.39**) The choice of construction method affects the conception of structural form. The traveler supports bridge segments until the span is complete. This avoids problems of stress reversal that is characteristic of the launching method. If the structure is supported before it is complete then the section can be varied to reflect the moment distribution. Launched bridges are of uniform depth to accommodate the stress reversal that occurs when the bridge acts as a cantilever as it is pushed out until it reaches the next pier and becomes a beam.[71] (**Appendix A-06, p.A.305, Fig. 55**)

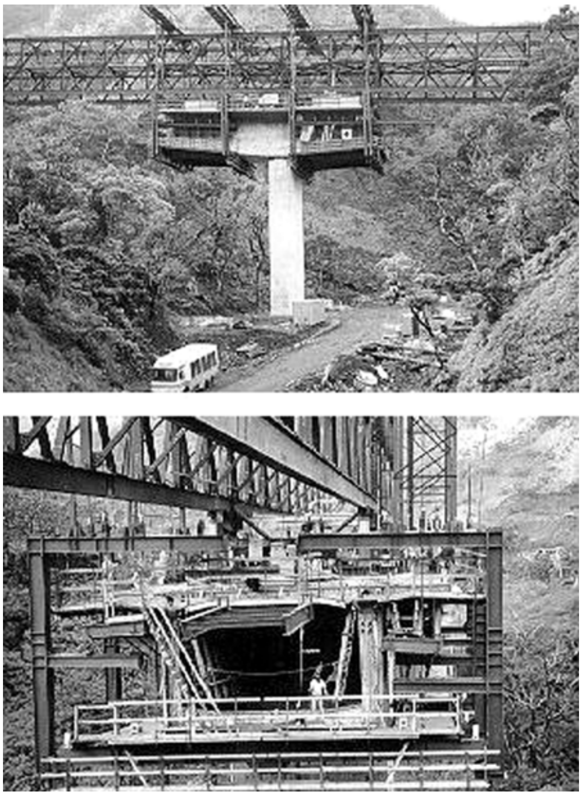
Fig. 4.39: H-3 North Halawa Valley viaduct, Oahu, Hawaii. Cast-in-place form traveler construction. Parsons Brinckerhoff Hirota Associates, 1996. (Sanders)

Section 4.2 used the case of the Britannia Bridge to demonstrate how government actions can influence the Function Pattern. (**Fig. 4.14**) In that case, the government demanded that the bridge not interfere with

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[70] Sanders.
[71] **Ref. Appendix A-06**.

shipping going through the Menaï Strait. This requirement could be interpreted volumetrically to define space in which the bridge could not occupy. This limited the forms and structural types the engineers could work with.

Public input can be an important factor directing form finding. The Figg Engineering Group, a bridge specialty design firm known for designing the Sunshine Skyway cable-stayed bridge at Tampa, Florida and the Long Key Bridge in the Florida Keys, makes it a policy to invite the public to design charettes for most all of the structures it designs. (**Appendix A-06, p.A.313, Fig. 67**) The firm values the fact that people will have to use and *see* their bridges every day. These design charettes influence the Function Pattern and the form finding process. Public involvement is also good policy because the process helps to minimize problems with public and special interest groups who may oppose the project.[72]

The structural system used for the Greek Temples is an example of passive socio-political impact on the Function Pattern.[73] Even though evidence exists that the Greeks were aware of and occasionally built arched forms, they did not use the arch to build temples and civic buildings. The Greeks could have used the arch to build greater spans that would have relieved the congestion caused by the closely spaced columns characteristic of their architecture. Clearly, the design of Greek temples was governed by culturally institutionalized thought patterns about what a temple should look like. These rules were more important than trying to use stone more efficiently.

4.8.3 Socio-Political Influence on Material Choice

Socio-Political Factors influence material choice. The influence of Socio-Political Factors on material costs is the most obvious aspect. Government policy can change the real cost of materials by imposing tariffs or by subsidizing an industry. Under Louis XVI, the French government subsidized the creation of a foundry for cast-iron at Le Creusot under the direction of William Wilkinson, an English iron founder.[74] Napoleon III similarly subsidized the development of the French aluminum industry.[75] However, subsidies do not necessarily lower costs. Iron costs during the reign of Napoleon Bonaparte limited the development of iron structures in France.[76] The subsidies likely created no incentive for the French iron industry to modernize and improve production.

The developer of structural materials has little control over such socio-political influences in the near term. Long-term change can be made through a coordinated campaign of lobbying governing bodies to remove restrictions to innovation. This process is typically carried out within the framework of lobbying groups made up of many groups and individuals with shared concerns. In this way, the 'voice' is stronger and more influential.

Another aspect of the influence of Socio-Political Factors is *cultural*. For the ancient Greeks, the perception of durability was a social criterion that informed their decision to use stone over wood. Similarly, during the late nineteenth century, plywood was inappropriately used in applications where it was subject to high moisture. The glues of the period easily

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[72] Jackson.
[73] **Ref. Appendix A-01**.
[74] Steiner, p19-20.
[75] Richards, p11.
[76] Steiner, p29.

degraded under such conditions, resulting in delamination failure of the plywood products. These failures attached a social stigma to plywood. It was perceived to be a cheap material even though its invention was driven by manufactures of fine furniture and pianos. This stigma has yet to be fully erased, even after superior glues were discovered in the first half of the twentieth century from which moisture resistant plywood products could be reliably manufactured. Today, veneered products are considered cheap, while the ancient Egyptians used veneering to make the most of valuable wood stocks. The perceived inferiority of wood products to other materials is an obstacle to developing wood products in applications more advanced than its use in sheet form in lightwood framing construction. Plywood had been used in technological advance aeronautic applications before the end of World War II. The first monocoque airframes were of plywood, not aluminum. A survey of wood applications today reveals that this is a material grossly under-developed, and the cultural stigma attached to it is part of the reason.[77]

Socio-political events also influence material choice by limiting supply. Just before World War I, the airship builder Schütte-Lanz chose to use plywood to build its airships in part because the supply of aluminum was limited.[78] Similarly, the price of aluminum and many other materials dropped since the end of the Cold War as Russia’s vast mineral resources have been exploited.[79]

Finally, socio-economic programs can also influence material choice. **Section 4.7** cited the example of Jörg Schlaich’s cable-stayed bridge design for the city of Calcutta. The local government required the designer to design the bridge so the local steel industry could fabricate it and local labor could be used to erect it. The government defined the material choice in order to support the local economy create jobs.

4.8.4 Patents

The patent system is an institution that can both enable and limit innovation. To one extent, the protections afforded by patents are critical to innovation. Their protections give a certain level of security to the persons who take risks to innovate and improve upon the state of the art. Without the security there would be less opportunity for an inventor to fairly profit from their work because there will always be opportunists and skullduggery in human affairs. Persons who make overly comprehensive patent claims that they do not exploit abuse the patent system and hinder innovation. Their patent prevents others from making meaningful improvements.

There are two periods in the history of structural materials when the patent system has been particularly active in the development of structural materials and forms. The first period is in the first half of the nineteenth century in the United States when a plethora of wooden trusses were patented.[80] In this case, it would seem that the patent system worked to the advantage of innovation. I have found no evidence that any one patent hindered development of others.

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[77] **Ref. Appendix A-04, p.A.209-A.224**.
[78] **Ref. Appendix A-04, p.A.226-A.227**.
[79] Ashby[2], p15 and 17.
[80] **Ref. Appendix A-03, p.A.86-A.90**.

The second period is in the latter half of the nineteenth century respective to the proprietary systems of reinforced concrete. At first, the protections enjoyed by the patent holders beneficially concentrated the small reinforced concrete market. This ensured that the companies taking the risk to establish this new material were not swept into insolvency by copycat competitors who may or may not have used inferior construction practices. As it was, this period had enough persons producing structures of poor quality that the industry had to defend against the build up of poor public perception. This is one of the reasons Hennebique published his in-house magazine *Le Béton Armé*. Nevertheless, the history of concrete construction indicates that these patent protections were also hindering innovation. Most major advances in the development of structural forms for reinforced concrete can be traced to the period just after 1900. Around this time, reinforced concrete design began to change from the proprietorships to a more open system as reinforced concrete design methods were published and codes written. Engineers developed the flat slab, thin shells and prestressed concrete after the main proprietary systems lost their semi-monopoly on the reinforced concrete design market.[81]

4.8.5 Socio-Political Influence on Material Development

Socio-Political Factors can encourage or discourage material development. The aforementioned subsidies provided by different French governments to the iron and aluminum industries were intended to encourage the development of those industries. Conversely, Queen Elizabeth's 1558 decree banning the use of most timber for making charcoal fuel effectively crippled the English iron industry for over one hundred fifty years.[82] One could argue that a long-term benefit of that decree was the development of coal as a fuel source in smelting iron.

Government sponsored research and pilot projects are also important factors in the general development of technology. Governments do not necessarily limit their spending because of economic or investment criteria. Government grants often fund academic research. Government also makes direct investments in new technology. For example, the Ohio state government is committed to installing one hundred FRP bridge decks.[83] Such an extensive program can lead to wider acceptance of that material for civil infrastructure applications. The experience gained from such a large pilot program leads to increased confidence in the material.

4.9 Knowledge and Technological Thought

Knowledge is what we know. Technological Thought is how we use what we know to create technological artifacts. There are two types of knowledge: quantifiable and experiential. Quantifiable knowledge is that which we can verbalize or record in written form. Therefore, quantifiable knowledge is transferable across time and space. Experiential knowledge is sensory, constituting our senses of touch, feel, smell, hearing and sight. Such knowledge is not easily transferable except through physical experience.

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[81] **Ref. Appendices A-05 and A-06**.

[82] **Ref. Appendix A-09, p.A.368-A.370.**

[83] Keller, p30.

Technological thought can similarly be defined in two categories. Cognitive thought and visual thought. Cognitive thought is verbal and visual thought is not. Richard Feynman, an American physicist, relates a story that clearly illustrates the difference between the two modes of thought:

> When I was a kid growing up in Far Rockaway, I had a friend named Bernie Walker. We both had "labs" at home, and we would do various "experiments." One time, we were discussing something – we must have been eleven or twelve at the time – and I said, "But thinking is nothing but talking to yourself inside."
>
> "Oh, yeah?" Bernie said. "Do you know the crazy shape of the crankshaft in a car?"
>
> "Yeah, what of it?"
>
> "Good. Now tell me: How did you describe it when you were talking to yourself?"
>
> So I learned from Bernie that thoughts can be visual as well as verbal.[84]

One last aspect of the cerebrum to consider here is that fuzzy concept of intuition or instinct. I would define engineering judgment as a combination of thought and intuition based on some level of knowledge. Intuition is based on experience.

Technological thought is unique to each individual. It is influenced by an individual's life experience and educational background. The importance of education is not so much the knowledge that is learned, but how one learns to learn, and how one learns to both *define* and solve problems. Various "schools of thought" evidence the power of the education process on thinking patterns. University professors such as Jean-Nicholas-Louis Durand[85] in France or Pierre Lardy[86] in Switzerland have had profound influences on the wider development of architecture and engineering disproportionate to their own personal works. Their students moved the development of architectural and engineering thinking forward.

The history of engineering knowledge is fairly well recorded in texts and historical summaries. Stephen Timoshenko's *History of Mechanics of Materials* is a particularly thorough source on the title subject. Greater understanding of structural theory and knowledge from materials science influenced the development of structural materials since the end of the eighteenth century. However, the historical record does not support the supposition that new structures are derived from structural theory. Thomas Telford built the Menaï Bridge using knowledge created for the purpose. Telford could have used existing mathematical methods to calculate the catenary curve of the chains but he would only trust the data from a physical model. Likewise, he had his own material tests performed to determine the properties of the wrought iron used.[87] Carpenters and engineers in America and elsewhere developed the truss before any mathematical methods existed to analyze it.[88] Robert Stephenson, with the aid of William Fairbairn and Eaton Hodgkinson, successfully

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[84] Feynman, p217.

[85] Villari; Pfammatter, p53-87. Durand led the development of the polytechnic model of architectural education from 1797 to 1836.

[86] Billington, p112-127.

[87] **Ref. Appendix A-02, p.A.53-A.55**.

[88] **Ref. Appendix A-03, p.A.83-A.92**.

developed the tubular beam even though beam theory at the time could not explain the buckling phenomena they discovered. This lack of knowledge influenced how they designed their experiments to find an appropriate form for this new structural type.[89]

Similarly, C.A.P. Turner's flat slab design was the subject of contentious debate in the United States. Critics irrationally claimed that such a structure did not obey Newton's Laws. Yet, Turner, and then Maillart, built such structures even though there was no adequate structural theory to explain how it worked. Turner and Maillart developed the knowledge to design such structures through experience. Maillart conducted sophisticated model tests to better understand the behavior of the flat slab. Each constructed project built with the flat slab offered further data to learn from and refine the design parameters for the flat slab.

The history of prestressed concrete represents an exception, and perhaps a pivotal point in the history of structural development. In this instance, it was precisely the knowledge of creep and shrinkage that led Eugène Freyssinet and Franz Dischinger to prestressed concrete. Prestressing has antecedents that predate this knowledge but it would be a mistake to describe these early experiments as successful in creating a new structural type. The example of prestressing must be examined in more detail and other studies made to determine whether the invention of prestressing represents a new paradigm in structural history. This new paradigm would be that knowledge, not Function, would be the enabler of future structural development.

I researched the subjects of knowledge and technological thought when starting this thesis because I saw them as the key to understanding *why* structural forms developed as they have. The case studies on the Menaï Suspension Bridge, Britannia Bridge and airships probe into these aspects. There are ample records available for all these case studies to give profound insight into the *thinking* of the persons involved in these projects. If we can understand their process of ideation – how they came up with new ideas and new structural forms – then we would be better able to do so ourselves. However, I have not delved deeply enough into the historical record of any one case study to make a quantitative analysis of what the persons involved were *thinking*. I focused on understanding the process of structural material and form development as broadly as possible. To do a technological thought study requires ample historical documents of a particular person's own writings. The analysis would have to incorporate a far superior understanding of psychology and philosophy than I can make claim to at this time.[90]

4.10 Influence Interaction and Form-Finding

4.10.1 An Influence Interaction Model

Chapter 03 defined a hierarchy of structural form and form types. System, Component and Element Form define the hierarchy. Detail Form, which includes connections, constitutes a fourth level of form. For reasons previously explained, this thesis only addresses the role of

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[89] **Ref. Appendix A-03, p.A.123-A.125**.

[90] Some engineers and technologists who have left ample documentation to begin such studies are: Thomas Telford, William Fairbairn, Robert Stephenson on the Britannia Bridge, Alexandre-Gustave Eiffel, Ferdinand von Zeppelin, Eugène Freyssinet, Ove Arup, and contemporaneously, Peter Rice and Jörg Schlaich.

Detail Form as it applies to System and Component level design. The generation of System, Component and Element Form is the product of a form-finding process. This process is variously affected by the influences this chapter defines. This chapter examined each influence individually and used examples of how these influences individually affect the development of structural forms and materials. This section examines how these influences fit collectively into the form-finding process. It will present a comprehensive *Form-Finding Influence Interaction Model*.

It was first assumed that the influences could be measured against one another and weighted. This is not possible to do for the form-finding model because the relative importance of each influence will depend on the function and context within which a particular form is created. Socio-political and economic objectives in particular will vary from one application to another; and from one period of time and place to another. Clearly, the economic criteria for building a dynamic structure such as the airframe of an airship are going to differ from those for a building.

The proposed model is organized by form-finding phases. Each phase corresponds to one of the three form types: Ideal Form, Constructible Form, and Implemented Form. I have created two illustrations to explain this model. **Influence Interaction Model$_1$** (starting p103) shows five examples of Ideal to Implemented Form progressions. The first example is Thomas Telford's cable design for the Menaï Bridge.[91] The second is Eaton Hodgkinson's development of an 'ideal' cast-iron beam section.[92] The third example shows a modified progression of the Britannia Bridge's tubular section.[93] It is modified to fit in the model as a logical sequence of design. In reality, the section was developed in parallel with knowledge about the properties of wrought iron and the buckling behavior of the tubular section. The fourth example is Luftschiffbau Schütte-Lanz's plywood airframe developed for its first ship, SL-1, and the subsequent System Form change for the production ship used from SL-2 onwards.[94] The last example is a hypothetical example for the 'ideal' longitudinal section of a beam subject to variable loading.

The following sub-sections use the aforementioned examples to examine each form-finding phase. This section defines where each influence enters into the form-finding process, and how that influence may affect either the generation or choice of form. **Influence Interaction Model$_2$** (starting p108) illustrates this process schematically.

4.10.2 Form-Finding Phase: Ideal$_1$ Form

The Ideal Form phase actually comprises two steps, distinguished here as *Ideal$_1$* and *Ideal$_2$*. The product of the Ideal$_1$ Form phase is the System Form. The System Form is derived from the influences of Function, Knowledge and Technological Thought. This phase is not material specific. The Function, or Function Pattern, defines the space limits. These space limits are those that must be spanned or enclosed, and those through which the structure cannot pass. Function also defines the Load Pattern that the structure must address.

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[91] **Ref. Appendix A-02**.
[92] **Ref. Appendix A-03, p.A.101-A.102**.
[93] **Ref. Appendix A-03, p.A.116-A.132**.
[94] **Ref. Appendix A-04, p.A.225-A.230**.

The Function Pattern for the Britannia Bridge is shown in **Figure 4.14**. It should be noted that Socio-Political influences on form are included in the Function Pattern, as explained in the section on Function in this chapter. In the case of the Britannia Bridge, the British Navy specified that the structure of the bridge could not occupy the spaces labeled S^1 and S^2 so as not to interfere with shipping traffic. Telford had to abandon his initial arch form for crossing the Menaï Strait for similar reasons almost forty years earlier. This led him to consider the suspension system. The Function Pattern of the Schütte-Lanz airship includes the gas volume to be contained, the structure's minimal mass, and the aerodynamic form to which the airframe must conform.

Statics and geometry govern the initial form in the case of the two beam examples. Hodgkinson was aware that it was advantageous to concentrate the mass of the material in the extreme fiber of a beam with only a slender web connecting the two. The longitudinal section of the second beam example is governed by the moment distribution under various load conditions. The Ideal Form is modeled on the idea of an active structure that changes form to adapt to different load cases. This is a realistic dream since so-called smart materials already exist that can return to their original shape after being deformed. There is also work on structural systems that will react to loads to maintain their overall shape. Recent research at the EPFL has been conducted on adjustable tensegrity structures. These structures have actuators that will self-stress the system to, for instance, maintain the slope of a roof under load. This is practical for such light and flexible structures in order to prevent ponding when subject to snow load.[95]

The product of the Ideal_1 Phase is a wire frame and surface diagram of the structural system like the example from Heino Engel's book shown in **Figure 3.6**. The system can be as simple as that shown for Telford's Menaï Bridge, or as complex as that shown for the Schütte-Lanz airship. Engel's System typology can be integrated into the process outlined in Model_2 as a useful design tool.[96] It can be expanded further to include structures other than buildings.

4.10.3 Form-Finding Phase: Ideal$_2$ Form

The Ideal_2 phase is material specific. A general structural designer will approach this phase differently than a material developer. The general structural designer must choose a material. To do so, the designer must define *suitability criteria* and weigh the relative merits of various materials to determine the one that best addresses structural and non-structural Function requirements. The developer has to define applicability criteria to determine whether the pre-selected material is amenable to a particular structural System. If not, then the System Form will have to be revised.

Choosing a structural material has become more complicated throughout history because of the increasing number of materials. There are over 40,000 materials available to the engineer.[97] Fortunately, the number generally used for construction is far more limited. Still, the introduction of FRP materials, increasing numbers of steel and aluminum alloys, different concrete admixtures, new high performance concretes and, the diversity of engineered wood

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[95] Fest, et al.
[96] An overview of his System typology is copied in **Appendix A-07**.
[97] Ashby[1], p1.

products all make the task of choosing materials less than obvious. For FRP materials, the designer has to choose between different matrix materials, fiber types, fiber architecture, and surface fleece products.

Michael F. Ashby's Material Selection system is another tool that can be integrated into this process.[98] This system is based on numerous charts with which materials can be compared to one another based on various selection criteria. Some charts are copied in **Appendix A-08**. These selection criteria are defined by relationships between various material properties and attributes, such as density, strength, cost, resistance to corrosion, and so forth. A profile of desired properties and attributes can be made for a given design. For instance, the material should have a low density, high strength, a modest cost, and resistance to de-icing salts. Ashby has defined a method that allows these criteria to be screened and ranked. First, the list of materials is narrowed by material properties to screen out materials that cannot meet the requirements. The remaining materials are ranked by their ability to maximize performance, which is generally limited by a combination of properties, such as strength and stiffness.[99]

Other factors to consider when making material choice are: the availability of materials; local construction labor and equipment markets; site accessibility; and construction issues that might affect material choice. An example of construction issues affecting choice is the need to lift a bridge in place in a short period because it traverses functioning infrastructure like a road or railway. To limit disruption, the bridge can be pre-assembled adjacent to its final position and moved at night. This would entail using a material like steel. Socio-political concerns also may be important, as in the case of the cable-stayed bridge Jörg Schlaich designed for the city of Calcutta. (**Fig. 4.33**)

Among the examples shown in Model$_1$, only the design of the Schütte-Lanz airframe began without the material choice already made. Schütte-Lanz chose plywood because it compared favorably with aluminum, though duraluminum was brand new when Schütte-Lanz started to make airships and, like Luftschiffbau Zeppelin, decided not to use this material until certain problems with it were resolved. Duraluminum had a tendency to age harden and become brittle. Furthermore, Schütte-Lanz thought that they could not be assured a reliable supply of aluminum, particularly when Zeppelin had the clear competitive advantage and connections to the industry. Wood was more plentiful and abundant.

The developer of materials must define applicability criteria to determine whether the material they want to use meets the requirements for a given structural System and Function. This requires including a number of issues such as formability and constructability attributes. This blurs the line between the Ideal Form phase and Constructible Form phase. However, the level of detail considered here should only include experiential knowledge of what does not work or what Component Forms are preferable for a given material.

In the Menaï, Hodgkinson, and Britannia examples, the material was largely determined by lack of material choice. Eaton Hodgkinson was clearly developing a specific material, cast iron. However, cast iron was the only material being used in England for heavy beam applications in mill buildings and bridges. Telford had no choice but to use wrought iron for a

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[98] Ashby[1], Michael F. *Materials Selection in Mechanical Design*.
[99] Ashby[1], p65.

suspension chain because it was the only material with the requisite tensile strength and toughness. Using wrought iron certainly meant paying a premium over other materials. By the time Robert Stephenson began designing the Britannia Bridge, cast iron had proved to be unreliable for beam applications. Wrought iron production had become cheaper due to the introduction of the hot blast furnace. The hot blast furnace nearly doubled the production capacity of the average iron-smelting furnace. This decreased pig iron prices so that the additional processes needed to make wrought iron were more affordable.

Once material choice and applicability are confirmed, the main purpose of the Ideal$_2$ phase is to determine the Component and Element Level Forms based on a criterion of least mass. Ideal$_2$ form is derived from Material Properties, Knowledge of analytic methods and experiential knowledge about appropriate forms, Technological Thought, and the consideration of Function Integration possibilities.

In the case of Telford's suspension cable, he understood the advantages of using continuous wire cables that would minimize connections and weight. Telford had many wire strength tests made to determine the cross-sectional area of wire he would need and what the best geometry of the cable would be to minimize the stress in the cable. The economy of the material needed in the cable had to be balanced by the cost of building the towers higher. The stress in a cable decreases by increasing its slope, i.e., increasing the distance from the bottom of the cable to the apex over the saddle.

Hodgkinson determined the relative strength of cast iron in compression and tension and proportioned the flanges accordingly. The tapered web reflects the disparity between the two strengths and the thinness reflects Hodgkinson's understanding that the web has only to be strong enough to resist shear and keep the two flanges separated. Hodgkinson would not have been aware of it at the time, but the web must also resist buckling. This was not a concern with cast-iron beams because the minimum casting thickness is too large for buckling to be a problem.

In developing the form of the Britannia Bridge, William Fairbairn determined that the upper flange of the tube was susceptible to buckling. He found that using a cellular flange could prevent this. Fairbairn and Hodgkinson continued the development of the tube together. They found that circular cells were the most efficient form for the top flange. It was necessary to only have a thick plate for the bottom flange at mid-span. The section of the tube is proportioned such that the train will pass *through* the beam, not over.

Schütte-Lanz assumed that the geometric form of its airframe would act like a lattice-shell and globally resist bending and torsion. They did not see the reason to make heavier, torsion resistant components like those used in the Zeppelin airships. (**Appendix A-04, p.A.207, Fig. 33**). Rather, they thought a linear, **I**-shaped section would be sufficient and the most weight efficient. The design of the structural System is intended to make a shell that would contain the gasbags without the need for the complex system of stiffening wires used in the Zeppelin airships. (**Appendix A-04, p.A.156, Fig. 9**)

For the hypothetical beam example, no material can yet change shape actively in reaction to applied loads on such a large scale. Steel is chosen for sake of argument. To accommodate all possible load cases, a beam with a curved bottom flange such that the depth of the beam varies with bending moment is preferable.

If one of the materials were FRP, the designer would have to determine the ideal arrangement of fibers with respect to the Element Form. This step may need to be addressed in more detail in the next form-finding phase.

The final step of the $Ideal_2$ phase is to confirm that the structure, which now has volume and mass rather than being a simple wire-frame and surface model, still accommodates the Function Pattern. If the process of proportioning the structural components requires an overly large section, it might interfere with the Function Pattern. The proportioned structure must meet strict weight requirements in the case of the airship. For the Britannia Bridge, the train must still fit through.

4.10.4 Form-Finding Phase: Constructible Form

The next step after defining the Ideal Form of a structure is to check that the structure can actually be made. Revisions will have to be made if it cannot. Whereas the influences in the Ideal phases were used to generate forms, the first purpose of the influences in the constructible phase is to check form. Only after a form has been found not to be producible are the influences of this phase used to generate form. Constructible Form is determined by the influences of Processing Technologies, Connections, and Construction Process. During this phase, Detail Form is created, and it may only be possible to define Element Form when considering Processing Technologies and Construction Process.

If an Ideal Form meets formability and constructibility criteria, then that form can be considered Constructible. In the given examples, Telford’s wire cable and the variable longitudinal section of the hypothetical beam are Constructible, therefore requiring no additional changes at this time.

The web of Hodgkinson’s ‘ideal’ section has to be thickened because it was not possible to cast elements as thin as the web that was structurally required. Similarly, a cellular bottom flange had to be included on the Britannia tubular section because there was a concern about the behavior of the long rivets that would have been required to rivet three-inch thick plates together. Solid plates of that thickness could not be rolled at the time. The Component level form had to be changed in both of these cases. These changes did not require making fundamental changes to the System Form.

In the case of the Schütte-Lanz airship, the connections between the Component girders were not sufficiently strong. This affected the overall strength of the ship. The connections had to be strengthened with duraluminum plates and prestressed stiffening rings had to be installed. These changes did affect the overall System Form because the structure was no longer a pure lattice shell, but a hybrid system. These changes had to be considered in the next phase to determine whether the perceived benefits of the original Ideal Form still existed.

The product of this phase is a Constructible Form that can be assessed by acceptance criteria, which are normally defined by economic parameters. If an Ideal Form is not also Constructible, the first remedial action is to change Component and Element Form. The general designer may solve the problem by changing materials. For both designer and developer, if the structure is still not constructible after these remedial actions, then it is necessary to start with a new System Form.

4.10.5 Form-Finding Phase: Implemented Form

The final phase of the form-finding process is to determine the Implemented Form. This determination is usually based on economic criteria. Economy may not translate into lower material or initial costs. In the case of the Schütte-Lanz airship, in-service performance conditions also have to be taken into account. A simpler, cigar-shape profile of the airframe would be cheaper from a constructive perspective. However, such a form would increase drag, thus reducing speed and maneuverability. Operating costs would also rise because of increased fuel consumption and longer flight times. For the Britannia Bridge, the cost of the novel tubular design was arguably excessive, but the railroad company was willing to pay a premium to build the bridge as expediently as possible. The company and its shareholders could only begin to make a return on their investment if the line was operational. The cost of time had to be considered in the economic equation.

Thomas Telford finally decided against using wire cables for two reasons. Wrought-iron wire was nearly 30% stronger than wrought-iron bars, however the wire cost over twice as much. Another factor that played in the decision was maintenance and life-cycle costs. Telford was concerned about how to reliably protect the wire from corrosion and, more importantly, how to even know if corrosion had begun in the interior of the cable. The bar-chain could be more readily inspected.

Hodgkinson’s ‘ideal’ beam section was modified in practice with a web that had parallel sides rather than tapered. The casting mold for parallel sides was easier to produce and the cooling temperature did not have to be so carefully controlled because the web did not vary in thickness. This modification simplified the fabrication process, thus reducing costs.

The final section of the Britannia Bridge had rectangular, cellular flanges top and bottom. The rectangular flange was easier to construct than the circular flange and, at the time, Fairbairn had already determined an acceptable final design with respect to the distribution of material using rectangular flanges. Construction would have been delayed if round cells were chosen because this final design work had not been done. Such a delay was unacceptable to the shareholders. Furthermore, the circular cells presented maintenance and security concerns because they would have made certain parts of the flange inaccessible to inspect for water infiltration and corrosion.

Once the stiffening rings and connection plates had been added to Schütte-Lanz’ innovative lattice shell airframe, the company determined that the weight advantage this system was supposed to have over the more conventional system of stiffening rings and longitudinal girders no longer existed. It did not make economic sense to stay with the original system because it was more complex to build. Schütte-Lanz did build one airship on the first System model. Once the ship was actually in service, it was found that the diamond-shaped dimples on the surface created by the tension of the exterior envelope stretched over the airframe, caused excessive drag. (**Fig. 4.40**) All future Schütte-Lanz airships built thereafter had a more conventional Zeppelin-type airframe with longitudinal girders and transversal stiffening rings. They continued to build their ships with plywood.

Finally, the most economic longitudinal section of an **I**-beam (by component cost) is with parallel flanges. This form is rolled directly and requires no further finishing. The ‘ideal’ form can be fabricated, but making a curved flange requires cutting off the flange of an **I**-beam,

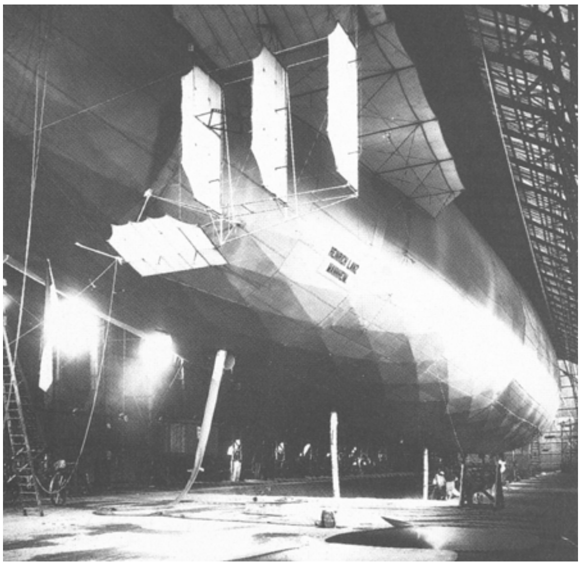
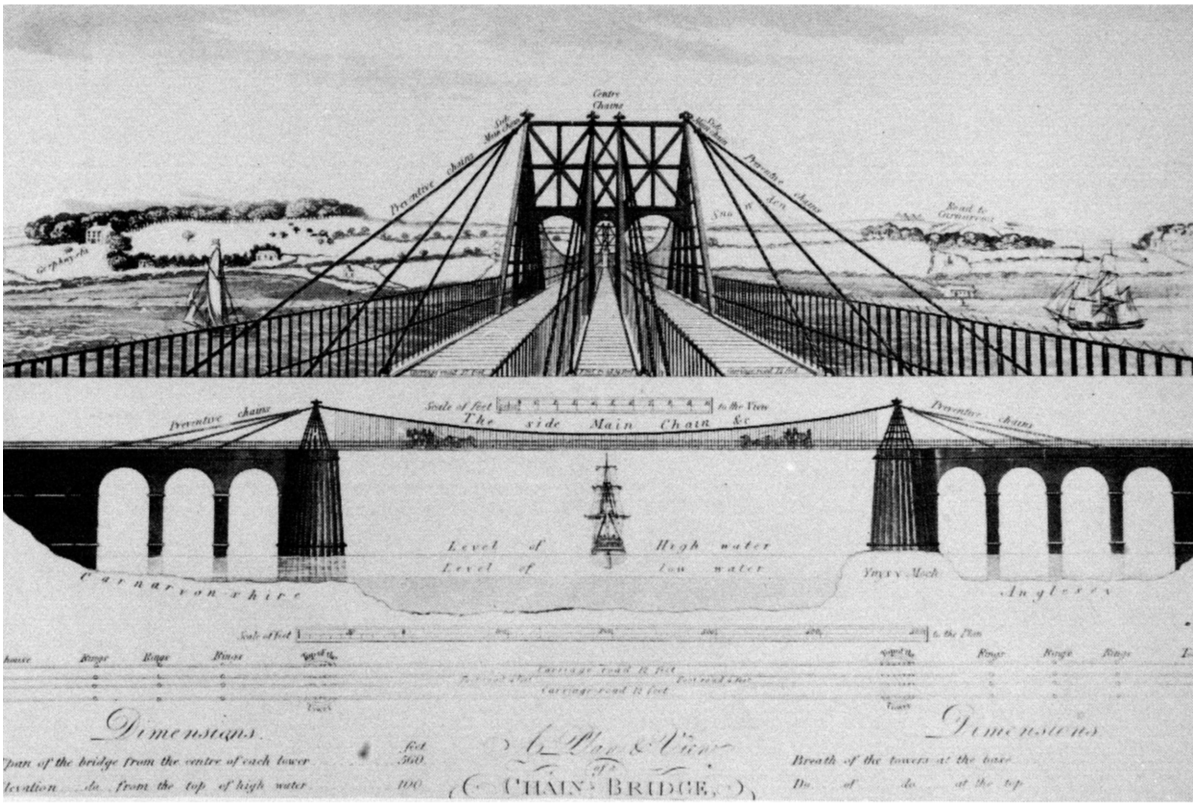


Fig. 4.40: View of drag inducing diamond pattern on the envelope of Schütte-Lanz airship SL-1. (Meyer[2])

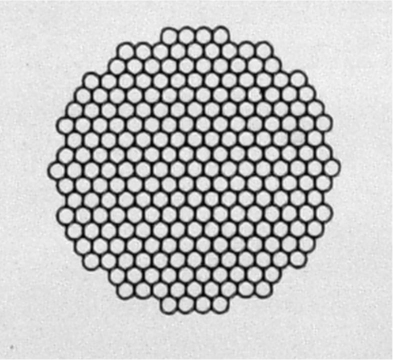
cutting the curved form in the web, rolling a separate bar for the curved lower flange, and welding that bar to the web. Alternatively, the beam can be made of two bars and a plate, but the plate still has to be cut to shape for the web and one of the bars still has to be rolled and now two flanges need to be welded, though there is less waste. This form requires too many processing steps to be economical except if insisted upon for aesthetic reasons. If a beam with variable depth is desired, then the least expensive solution is to taper the section linearly, which requires two simple straight cuts be made to the web of an **I**-beam and two bars be welded to the web to make the flange. This form was used in the Embankment Place Building shown in **Figure 4.37**. The cost was justified in this case because the tapered flanges allowed the building services to be routed in the triangular voids, thus minimizing the floor-to-floor depth such that one more floor was built in the fixed-height of the building than if conventional beams had been used.

When the constructible form does not meet economic defined parameters, the designer can first try using a different Constructible Form, or try using different processing and connection technologies. Furthermore, the influence of life-cycle cost analysis is becoming more important today, which changes the traditional approach of simply analyzing the bottom line cost of the material or the finished component. If the constructible form still does not meet the economic criteria to move to production, then the material choice must be changed or the process must begin again with a new System.

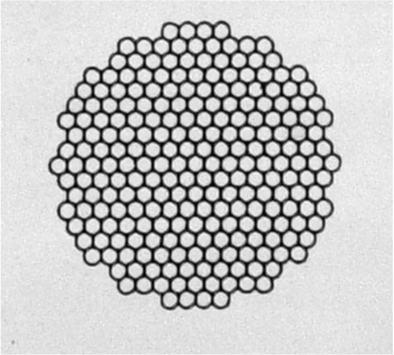
FORM-FINDING INFLUENCE INTERACTION MODEL$_1$, Example 1
The Menaï Suspension Bridge, 1826



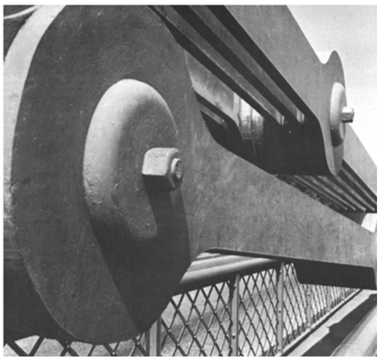
Ideal$_1$



Ideal$_2$



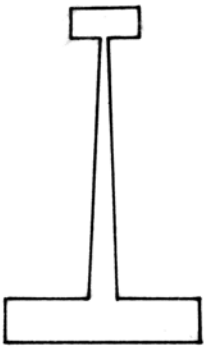
Constructible

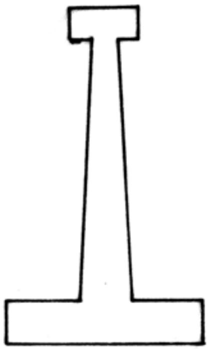


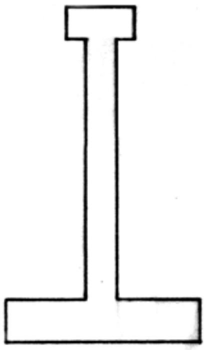
Implemented

FORM-FINDING INFLUENCE INTERACTION MODEL$_1$, Example 2
Eaton Hodgkinson’s ‘Ideal’ Cast-Iron Beam Section, 1830


Ideal$_1$


Ideal$_2$


Constructible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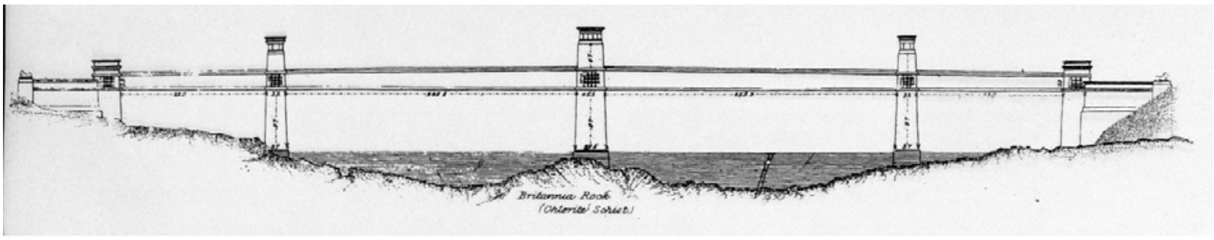
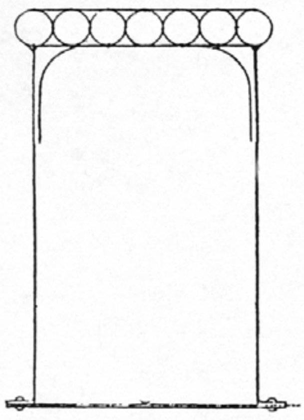
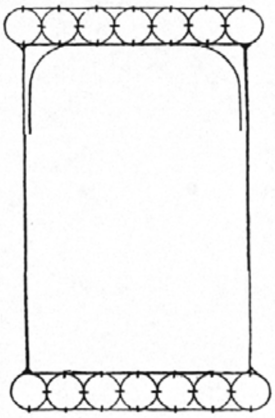
FORM-FINDING INFLUENCE INTERACTION MODEL$_1$, Example 3
The Britannia Bridge, 1850



Ideal$_1$


Ideal$_2$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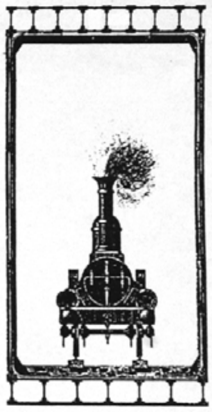
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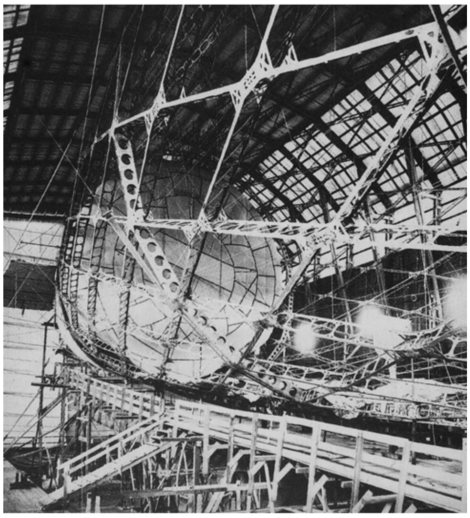
FORM-FINDING INFLUENCE INTERACTION MODEL$_1$, Example 4
Plywood Airframe of the Schütte-Lanz Airship, 1911-1913

Ideal$_1$

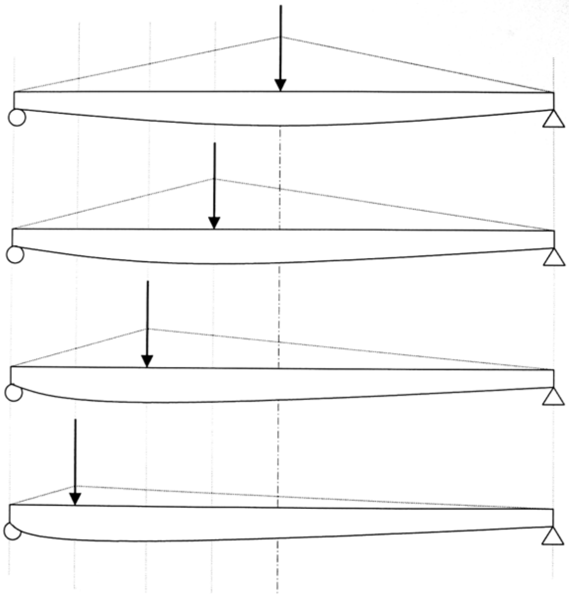
Ideal$_2$



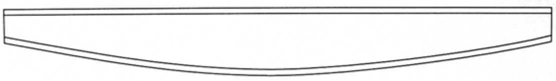
Constructible

Implemented

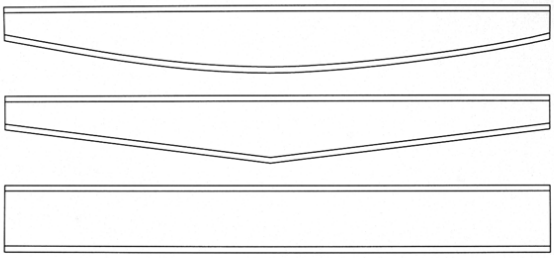
FORM-FINDING INFLUENCE INTERACTION MODEL$_1$, Example 5
Longitudinal Section of a Hypothetical Beam



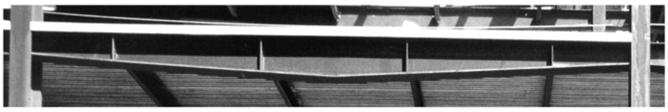
Ideal$_1$



Ideal$_2$



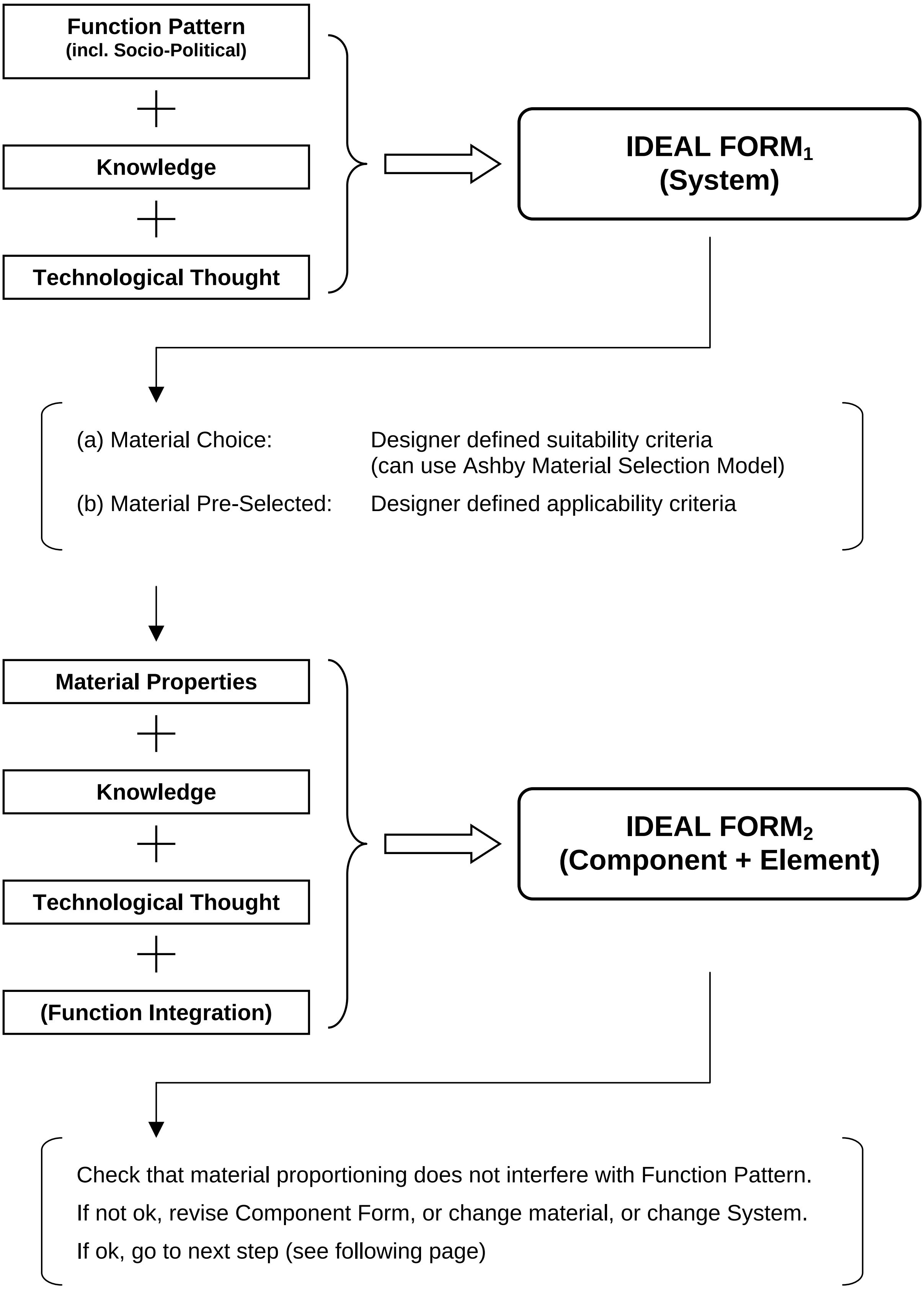
Constructible



Implemented

FORM-FINDING INFLUENCE INTERACTION MODEL$_2$ STARTS ON NEXT PAGE

FORM-FINDING INFLUENCE INTERACTION MODEL$_2$



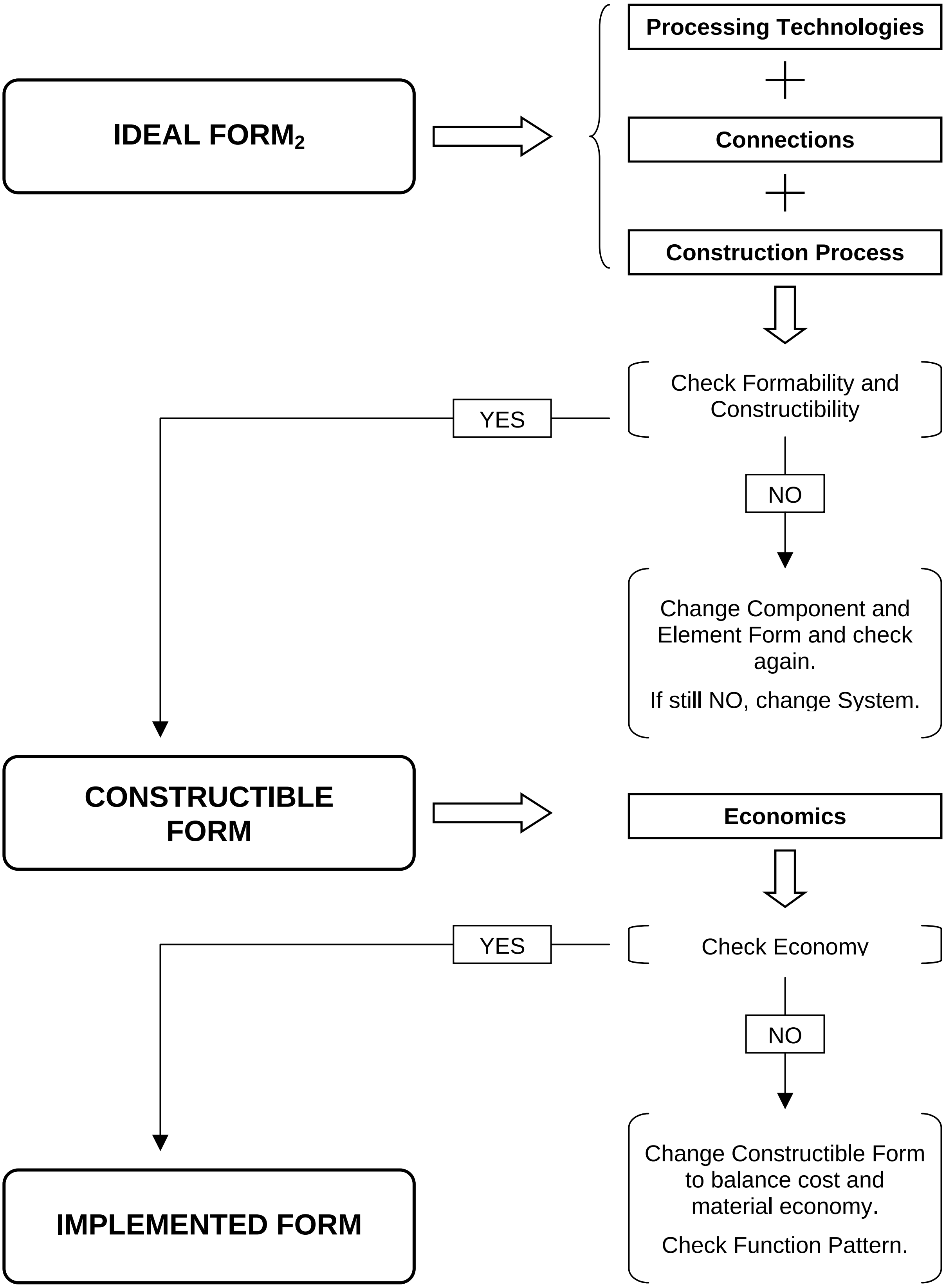
(a) Material Choice:	Designer defined suitability criteria (can use Ashby Material Selection Model)
(b) Material Pre-Selected:	Designer defined applicability criteria

Check that material proportioning does not interfere with Function Pattern.

If not ok, revise Component Form, or change material, or change System.

If ok, go to next step (see following page)

FORM-FINDING INFLUENCE INTERACTION MODEL$_2$



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MATERIAL-ADAPTED STRUCTURAL FORM

05

5.1 Introduction

This project began with the assumption that *structural properties determine material-adapted form*. I interpreted material properties to specifically refer to structural properties at that stage. A simple interpretation of this view would be to ascribe forms, or applications, to materials that best exploit a material's structural properties. For example, a material strong in compression but weak in tension should be used in columns or arches, but not suspension cables or beams. After subsequent research, I concluded that this is only partially true, and such a prescriptive method seems unduly restrictive to the process of form-finding. The influences described in **Chapter 04**, which are not limited to material properties, variously affect the process of form-finding and, therefore, material-adapted form. This information led me to begin this thesis with the hypothesis that *structural properties do not unilaterally determine material-adapted structural form*.

This chapter will define *material-adapted form*. I will examine the concept of form more philosophically, define the so-called *nature* of materials, and define the qualities of good structure.

This chapter addresses the unresolved issue of substitution by examining whether this is an appropriate term and if it is accurate to say that each material is first used substitutionally. It is appropriate to include this section here because it relates directly to the subject of material-adapted form and the historical development of structural form.

5.2 The 'Nature' of Structural Form

This section addresses the question of what *appropriate form* means, which is not self-evident. *Appropriate* and *material-adapted* do not necessarily mean exactly the same thing, but whatever *material-adapted* is, it must be appropriate.

The idea of form as the characteristic principle of a thing dates to at least 550 BC.[1] The aspect that form is a characteristic principle needs to be examined further because when we speak of *structural* form there is the inherent idea that the form must reflect its structural purpose. Why should structure look like structure? What should structural form look like? Form is ultimately the conceptual product of our imagination, and the material product of our ability to manipulate and process materials. Therefore, *structural form has both metaphysical and mechanical limits*.

---

[1] Whyte, p230.

In 1214, Robert Grossteste, an English philosopher, defined form as a thing that is what it is.[2] This definition struck me to mean that form is an inert concept whose shape is specious or without materiality. Samuel Taylor Coleridge, a nineteenth-century English metaphysician and poet, makes this interpretation more explicit. He wrote, "No work of true genius dares want its appropriate form. The form is mechanic, when on any given material we impress a predetermined form, not necessarily arising out of the properties of the material; as when to a mass of wet clay we give whatever shape we wish it to retain when hardened."[3] There is a problem with Coleridge's concept. It is not clear how the form made of clay does not arise out of that material's properties, nor why such a shape should be inappropriate. However, the concept that a thing is what it is could be interpreted to mean that *appropriate* form is merely that which is producible. Therefore, appropriate structural form need only be that which satisfies the most basic security and serviceability requirements, such as a large irregular stone placed on two supports to make a bridge. (**Appendix A-09, p.A.361, Fig. 1**) If it functions, it is an appropriate use of material.

This interpretation of Grossteste and Coleridge's definitions of form raises a point that perhaps they did not intend; that the *process* of making form is an important, if not the most critical, quality of form. This idea diverges from Coleridge's because Coleridge does not recognize the fact that the act of manipulating material relates directly to a material's processing attributes and their relationship to material properties. Nevertheless, Coleridge explicitly refers to the final state of an artifact, when the clay hardens in this case. Since the form was created when the material was in a different physical state there is an apparent disconnect between material properties and the final form. Therefore, *form is what it is,* except*, it has an inherent characteristic of the process by which it was made*.

In 1593, Francis Bacon stated, "The Form of a thing is its very essence." He defined form as the objective conditions on which a sensible body or quality depends for its existence and the knowledge of which enables it to be fully reproduced.[4] Bacon's concept of a sensible body is appealing. The stone used to make the bridge mentioned above may have been formed in a sensible way geologically, but as a structural component, it was simply a conveniently found object *suitable* for the purpose. The stone cannot be reproduced, though suitable stones could be found to make other bridges. Either the maximum size stone that can be found and moved, or the ultimate strength and dimensions of the stone will limit the size of such bridges. As a technological thought, it was a great and expedient idea to use a conveniently found object to traverse an obstacle, but its use is limited unless it can also be sensibly extrapolated from this simple bridge that perhaps other materials can be used, or longer bridges can be made using the same material if used in a different way. Therefore, *form has limits related to the availability of materials, the ability to process and build with those materials, and material properties*.

When Bacon says that the "Form of a thing is its very essence," it seems that he sees form similarly to Grossteste, except we know that Bacon, unlike Coleridge, interprets form to also reflect knowledge and sensibility. Therefore, form is more than just what is apparent, its physical outward appearance. S.P.F. Humphreys-Owen explains, "Our appreciation of form

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[2] Whyte, p231.
[3] Coleridge, pp46-47, copied in De Zurko, p118.
[4] Whyte, p230.

is partly sensory, but we can be helped by measurement and calculation to gain some confidence that what we perceive is not entirely unconnected with the outside world… The science of Geometry [could] interpret form, by discovering that the essence of the form is a certain relationship between dimensions in space. Geometry is an abstraction of all properties of matter other than that of 'occupying space.' Other sciences introduce, successively, other properties."[5] These other sciences can include mechanics, dynamics, and physics. Humphreys-Owen is inferring that a material has *Gestalt* qualities; what Konrad Lorenz described as "the characteristic quality of the whole can be dependent on the universal interaction of literally all its parts, thus proving the naïvety of the… atomistic assumption that a part, though isolated experimentally, would behave exactly as it did in the context of the whole."[6] Christian von Ehrenfels first discussed the concept of Gestalt-qualities around 1890. These qualities were used to define a theory of perception in the early twentieth century by Max Wertheimer, Wolfgang Koehler, Kurt Koffka, and others.[7] We can interpret this argument to mean that Coleridge assumes the clay will behave the same regardless of what form it is in. However, the idea of a Gestalt-quality means that form is a part of a whole, not *the* whole. Therefore, form does affect the behavior of the material. This is true in structural engineering, as evidenced by Robert Maillart's Tavansa Bridge in Graubünden, Switzerland.[8] (**Appendix A-05, p.A.259, Fig.37**) Maillart learned from previous bridges at Zuoz and Bilwil that the concrete in the spandrels of these arch bridges was not in compression. (**Appendix A-05, p.A.259, Fig.36**) This material was not helping to transfer load to the arch, so Maillart eliminated the material. He thus created a new form of arch specific to reinforced concrete. The deck over these openings would be subject to bending and thereby tension, which would not be acceptable in a stone bridge. The concept of a Gestalt-quality seems to embody the idea of what *appropriate* structural form could be. However, the essence of a structural form, its Gestalt-quality, must be more specifically elucidated; the following sections will do so.

5.3 The 'Nature' of Structural Materials

5.3.1 Opening Thoughts about the Nature of Materials

In the nineteenth century, Eugène-Emmanuel Viollet-le-Duc, a French architect, tried to understand and rationalize how the use of iron in architecture changed the technics, formal organization, and aesthetics of architecture. While contemplating the unique qualities of iron and the differences between it and stone, Viollet-le-Duc wrote, "To build, for the architect, is to make use of materials in accordance with their qualities or their own nature."[9] Other prominent designers, both engineers and architects, have used the concept that a material has a particular 'nature.' The use of this term has been variously employed to both explain and justify what Italian engineer Pier Luigi Nervi describes as the "correct" way of building.[10]

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[5] Whyte, p8.
[6] Whyte, p157.
[7] Whyte, p230.
[8] **Ref. Appendix A-05, p.A.258-259**.
[9] Viollet-le-Duc^3, p106.
[10] Nervi^2, p1.

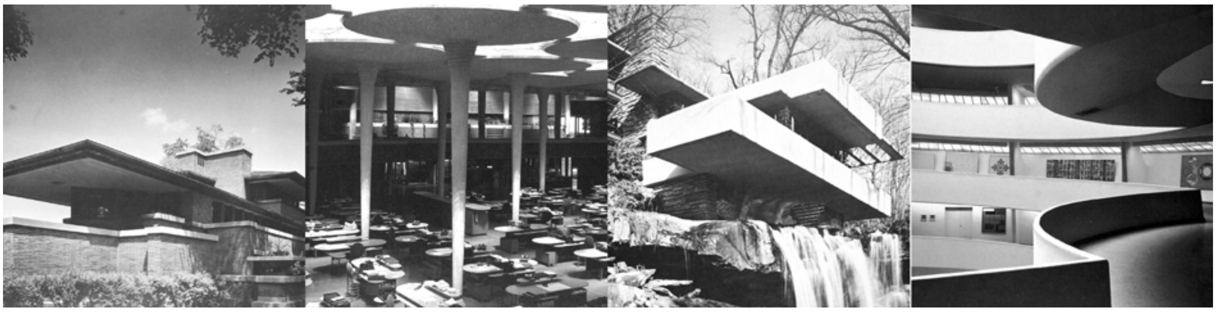

Fig. 5.1: Buildings by American architect Frank Lloyd Wright. (a) Robie House, Chicago, Illinois. 1909. (b) Johnson Wax Administration Building, Racine Wisconsin. 1936. (c) Fallingwater, Bear Run, Pennsylvania. 1934. (d) Guggenheim Museum, New York. 1959. (Futagawa[1]; Lipman; Futagawa[2]; Futagawa[3])

But what *is* the nature of a material? What quantifies a structural form as *correct* versus *incorrect*?

Frank Lloyd Wright wrote, “Bring out the nature of the materials, let their nature intimately into your scheme…. Reveal the nature of the wood, plaster, brick or stone in your designs… they are by nature friendly and beautiful.”[11] Wright’s interpretation of the nature of a material seems to focus on the aesthetic qualities of a material. He clearly is recommending that materials be shown and not hidden, but in what way? The body of his work – Robie House, the Johnson Wax Building, Fallingwater, and the Guggenheim Museum for example – indicate that Wright understood the constructive attributes of materials. (**Fig. 5.1**) The brick courses of the Robie House show the courses of unit masonry for what they are, emphasizing the material’s origin of the earth by filling in the vertical mortar joints that can be symbolically interpreted as being actual layers of earth. The horizontality of the material emphasizes this connection with the earth and that it is built in layers. In the Johnson Wax Building, Wright conceived of giant mushroom columns whose form reveals the plastic nature of concrete when it is formed. He accents these qualities further at Fallingwater, rounding the top-edges of the parapet walls lining the daring cantilevers that are characteristic of this building. Finally, Wright aesthetically and constructively pushed the limits of concrete’s plasticity in the Guggenheim Building where he used curvilinear forms throughout. From Wright’s work, we can extrapolate two qualities that describe the nature of a material, its aesthetic appearance, and the relationship between its aesthetic appearance, its form, and its processing and constructive attributes. However, Wright was writing about the beauty of the finished state of a material. What is the connection between material properties and the form in which the material is used?

Louis I. Kahn proposed the notion that materials can *tell* us what form they want to take. Kahn wrote, “Realization is realization of form, which means a nature. You realize that something has a certain nature.”[12] Kahn seems to be completing Wright’s thoughts. Kahn insinuates a connection between the constructive attributes of a material and form. This connection is evident in Wright’s work. However, Kahn later starts a hypothetical conversation with a material, in this case, brick. Kahn asks, “What do you want Brick?” and Brick answers, “I like an arch.”[13] The idea that a material can tell us what form it wants to be

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[11] Wright, p55, from reprint of article written in Architectural Record, March 1908.
[12] Kahn, from Lobell, p40.
[13] Kahn, from Lobell, p40.

in, as Bjørn Normann Sandaker, a Norwegian architect and theoretician, appears to support by referring to a material's *raison d'être* and stating that structural materials are "likely to take" certain geometrical forms,[14] is absurd. This is a false premise since a material, unless it is biological, cannot *take* any form unless a human conceives of it *and* can process the material into that form. This concept presupposes that a material 'wants' to take one form or another. Perhaps this is a useful intellectual tool to gain a better understanding of a material. Perhaps such thinking helps to introduce an element of metaphor or symbolism in the use of material, as in Wright's use of brick in Robie House. However, the reality is that man-made forms are products of human imagination. The material does not really 'tell' us what form it wants to take, people do.

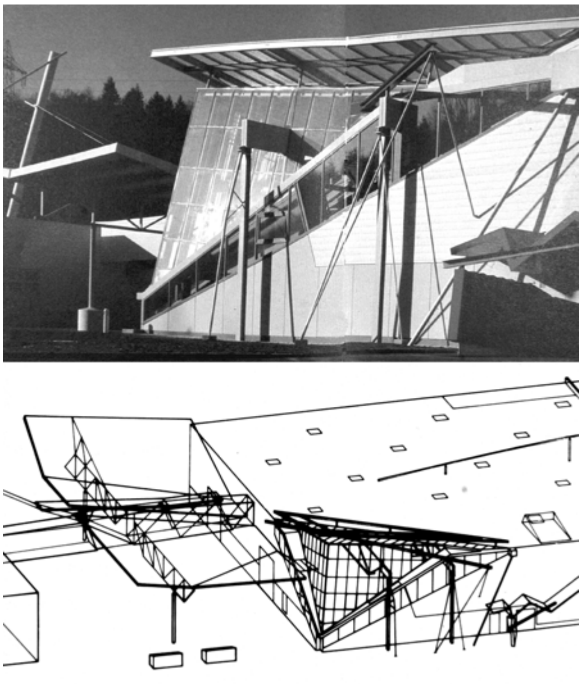

Fig. 5.2: Funderwerk, St. Veit/Glan, Austria. Coop Himmelb(l)au, 1989. (Guiheux)

As a tool of form-finding, the concept that a material has a nature and that this nature 'tells' us what form the material 'wants' to be fails to offer quantifiable parameters by which to generate form. The material's 'want' can of course be substituted for the more accurate term of what form is *appropriate*. However, this still leaves us guessing what the nature of a particular material is. What Viollet-le-Duc, Wright and Kahn mean when they refer to the *nature* of materials needs to be defined more concretely. It appears that these esteemed individuals have simply substituted this concept in the place of a meaningful description of how they think about and create form.

Sandaker examines the concept of conceiving physical form irrespective of material. He cites the deconstructivist architecture of the Austrian architectural design firm Coop Himmelb(l)au. According to firm partner Wolf Prix, they do not consider material until they have to "realize" the project, "when the idea is being transposed into reality."[15] The architecture of Coop Himmelb(l)au certainly appears to have been conceived irrespective of material, but its final form *is* material. (**Fig. 5.2**) Sandaker concludes from his examination of the writings of Viollet-le-Duc, Wright, Kahn, and Prix that the relationship between structural form and the 'nature' of forms can mean one of two things: Form "resides" in the material, and is made explicit by respecting the qualities and properties, or "the nature", of that material; Form is conceived irrespective of the material, and is as such free to evolve without preconditions of a specific material realization.[16]

Sandaker's first statement is superfluous because he does not present a coherent definition of what the nature of a material is. He repeats the mantra of Kahn and ignores his own

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[14] Sandaker, p21 and 60.
[15] Sandaker, p52.
[16] Sandaker, p53.

observations that there could be a more substantial definition of what the nature of a material is. He observes that Viollet-le-Duc must mean to use material as *efficiently* as possible when Viollet-le-Duc writes, "The methods of the builder must accordingly vary by reason of the nature of the materials he is working with."[17] Sandaker's reasoning weakens when he interprets the influence of processing technologies on the nature of a material as a parameter that made the idea of a material having a nature "a somewhat foggy concept."[18] On the contrary, processing technologies and the construction process may be the key to understanding what the nature of a material is.

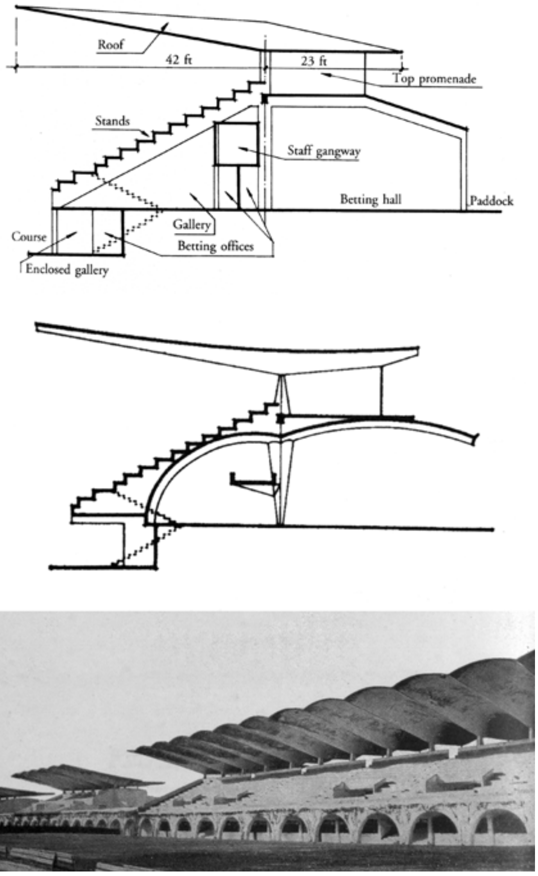

Fig. 5.3: Initial (top) and final (middle) conceptual designs for the Madrid Racecourse viewing stand. Eduardo Torroja. 1935. (Torroja)

Sandaker cites the design methodology of Coop Himmelb(l)au to justify his conclusion that form is free to evolve without preconditions of a specific material realization. However, Sandaker records Himmelb(l)au's Prix saying that the conception of form occurs irrespective of material *until* [emphasis mine] the form must be realized. Essentially, Prix is illustrating phases one and two of the form-finding process presented at the end of **Chapter 04**. To make the structure a reality requires materials be chosen, which in turn requires suitability criteria be defined that specifically address material properties. If material properties effectively define the so-called 'nature' of a material, as Sandaker concludes in his first hypothesis, then Sandaker's second hypothesis is actually part of the same philosophy. To say form is free of material when material is not considered is self-evident. The question is, how does material affect form once it is considered? How does that initial form affect material choice? **Chapter 04** addressed these questions. What still lacks is a coherent definition of what the *nature* of a material is, and what makes a form *appropriate*.

5.3.2 Clarifying what the 'Nature' of a Material is

I alluded above to the fact that the idea of there being a nature of materials is not clear the persons who use it cannot express in more quantifiable terms what they mean or how this concept influences the process of form-finding. Nervi reinforces this impression when he writes, "A structure unveils its nature and the most interesting aspects of its behavior to its creator, designer, and builder. It tells very little to the man who watches it from the outside or examines it through photographs."[19] This is unhelpful. Though Nervi explains his concept of

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[17] Sandaker, p42; Viollet-le-Duc^3, p106.
[18] Sandaker, p50.
[19] Nervi^2, p.vix.

the correct way of building throughout his book *Structures*, he never specifically explains what the nature of materials is.

Eduardo Torroja, a Spanish engineer and contemporary of Nervi, gives some insight into why it is so difficult for a creative designer to explain how they arrived at a particular form. Torroja wrote that the time it took him to refine his design for the Madrid Racecourse (1935) from initial concept to final form took a matter of minutes.[20] (**Fig. 5.3**) The difference between the two designs and the amount of detail and complexity of problems considered in the intervening iterations is enormous. How is a designer to record all of the different parameters that are processed by the brain to make the decisions that lead up to the final concept? This is often the nature of design, and is why it may be so hard to explain to others how the design was generated. Therefore, we have to rely on other things these designers are saying to better understand what they mean by the 'nature' of a material.

Viollet-le-Duc wrote, "There are in architecture… two indispensable modes in which truth must be adhered to. We must be true in respect of the programme, and true in respect of the constructive process. To be true in respect of the programme is to fulfill exactly, scrupulously, the conditions imposed by the requirements of the case. To be true in respect of the constructive process is to employ the materials according to their qualities and properties."[21] **Section 5.4** addresses Viollet-le-Duc's first requirement. The focus here is on what Viollet-le-Duc means when he says that materials should be employed according to their qualities and properties. *Qualities* and *properties* sounds like a substitute for the word *nature* in this context.

Viollet-le-Duc was principally interested in developing an architectural language that included and expressed iron structure. Pondering the use and application of iron in buildings, Viollet-le-Duc wrote,

> If iron is destined to play an important part in our buildings, let us study its properties, and frankly use them, with that sound judgment which the true artists of every age have brought to bear upon their works.[22]
>
> Provision should be made for the contraction of the iron and for its changes, and it should only be used under conditions favourable to the development of its properties. When, therefore, we would build masonry vaulting on iron, the latter should retain its liberty of movement and be able to expand without rending the concrete envelope which it supports. The fastenings should remain visible – clearly seen – so that, should any part give way, it may be promptly repaired. If we propose to use iron conjointly with masonry, we must give up the traditional methods of Roman structure. We have no longer to contemplate erecting buildings based on inert immoveable masses, but to provide for elasticity and equilibrium. The distribution of active forces must replace an agglomeration of passive forces. For the attainment of these results, the study of the structure of the French mediæval buildings can be of great service, for the architects of that period had already substituted the laws of equilibration and elasticity for those of Roman structure.[23]

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[20] Torroja, p8.
[21] Viollet-le-Duc^1, p448.
[22] Viollet-le-Duc^2, p65.
[23] Viollet-le-Duc^2, p67.

> It is possible by means of iron, employed as sinews and tendons, to construct vaulting of little rise and great span.[24] (**Fig. 5.4**)
>
> It is evident that in a construction of this kind everything should be prepared in advance. The various parts of the work can be executed in manufactories or special workshops, and be brought to the building ready fitted, so that they can be raised into place without further trouble.[25]

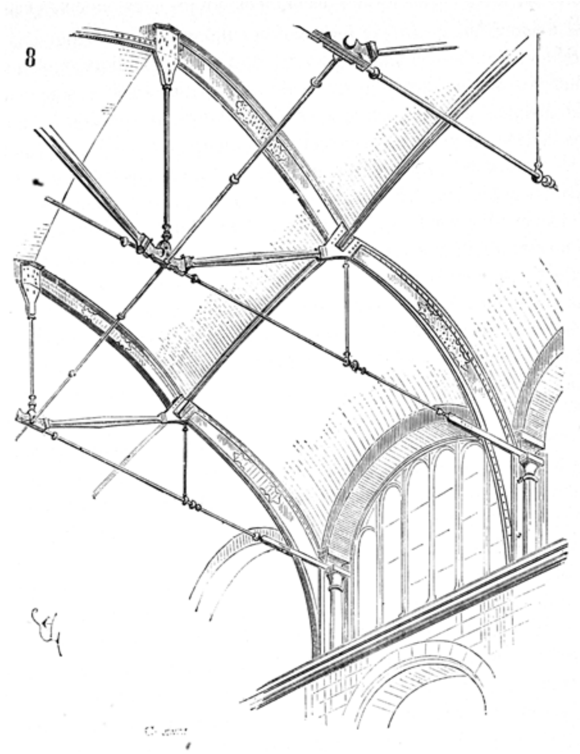

Fig. 5.4: Iron vault design, Eugène-Emmanuel Viollet-le-Duc. (Viollet-le-Duc[2])

Viollet-le-Duc demonstrates an appreciation for the particular properties of iron that differentiates that material from stone. Iron's tensile strength seems to be of greatest interest to him, perhaps because this property directly contravenes and is in figurative tension with the characteristics of stone construction. Viollet-le-Duc states that iron ought to be visible not because of an overriding philosophy of structural 'honesty,' though this is part of it, but rather because iron is more susceptible to degradation than stone. Iron must therefore be accessible for inspection and repair.

Viollet-le-Duc recognized that historical precedence could be useful in inspiring the search for new form, similar in idea to this thesis. Viollet-le-Duc understood that the strength and stiffness of iron would allow traditional forms to be manipulated in ways that were not possible in stone because of the capacity to introduce tensile forces into the structure. Lastly, Viollet-le-Duc appreciated the fact that the construction process needs to be incorporated into the conception of these structures.

Nervi wrote, "We all have a tactile sense and subconscious appreciation of the physical qualities of the materials most commonly used, so that seeing them correctly used, according to their natures, influences the general impression produced by a work of architecture."[26] If interpreted correctly, Nervi associates the nature of a material with its physical and tactile properties. Unfortunately, Nervi describes this understanding of material as a "sense and subconscious appreciation," which is again unhelpful to our own understanding of what he means. Nervi wrote the following about reinforced concrete,

> Reinforced concrete is the best structural material yet devised by mankind. Almost by magic, we have been able to create "melted" stones of any desired shape, structurally superior, because of their tensile strength, to natural stone. Because of its high compressive strength, its exceptional weather resistance, its constructional simplicity, and its relatively low cost, reinforced concrete is truly

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[24] Viollet-le-Duc[2], p67.
[25] Viollet-le-Duc[2], p81.
[26] Nervi[1], p3.

> the most interesting and promising structural material available to mankind today.[27]

For Nervi, concrete's high compressive strength, tensile strength, exceptional weather resistance, constructional simplicity, and relatively low cost constitute, at least partially, the nature of reinforced concrete. Nervi reserves his greatest admiration for the material's processing and constructability attributes. Nervi, who was a builder as well as designer, values the capability of forming concrete into "melted" forms. This appears to be the root of Nervi's understanding of the nature of reinforced concrete.

English engineer Peter Rice echoes Nervi's view of materials. When writing about the differences between the structures of the Pompidou Center in Paris (1976), and the Lloyd's Building in London (1985), Rice described steel as an "articulated" material, while concrete is monolithic. (**Figs. 5.5 and 5.6**) "A steel building," Rice wrote, "is an assembly of elements, the sizes of which are determined by the process of manufacture and the method of transport…. In concrete, almost the reverse is true. Concrete is a cast material. This means that there is by the nature of the construction a continuity between members when they are cast in place."[28] Based on the writings of the aforementioned engineers and architects, I conclude that *a material's processing and constructability attributes are fundamental components of its nature; these characteristics partially define a structural form's Gestalt-quality*.

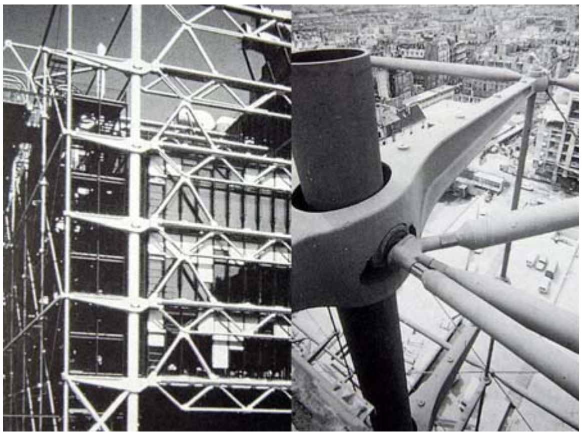

Fig. 5.5: Steel structural system of the Pompidou Center, Paris, Richard Rogers and Renzo Piano, architects, and Peter Rice of Ove Arup Ltd., engineer. 1976. (Rice)

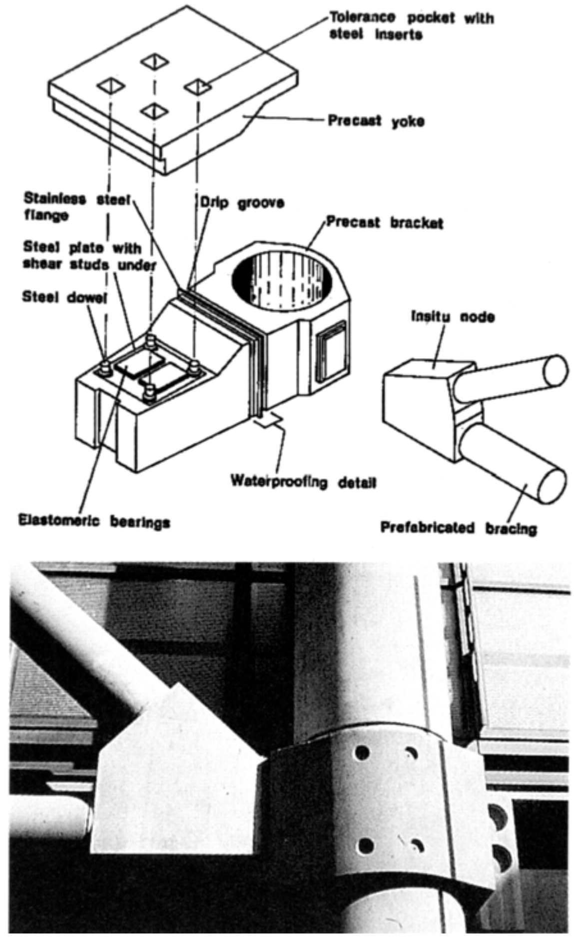

Fig. 5.6: Reinforced concrete structural system of the Lloyds Building, London, Richard Rogers, architect, and Peter Rice of Ove Arup Ltd, engineer. 1984. (Rice)

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[27] Nervi^2, p28 and 30.

[28] Rice, p115-116.

5.3.3 Defining the Nature of Materials and Appropriate Form

Fig. 5.7: Underside of floor slab of the Gatti wool factory showing isostatic stress lines, Rome, Pier Luigi Nervi. 1951. (Nervi^2)

The nature of a material is defined by:

- *material properties*
- *processing and constructability attributes*

Limits of form can be extrapolated from these two qualities. These limits are created either by the limits of the material itself – its strength, stiffness, etc., or by our ability to create a particular form. These properties do not define, in a definitive or quantifiable way, what forms are *appropriate* for a particular material. Viollet-le-Duc, Nervi, Wright and Kahn are of the consensus that the form should reflect the qualities of a material's nature. The **I**-beam clearly expresses that steel is equally strong in compression and tension and that it can be formed by some linear processing method that makes components of uniform section. A reinforced concrete shell expresses that concrete has a high compressive strength and that it can be made into complex, monolithic forms that can only be possible if the material is made and formed *in situ*. The combination of material and form in both examples appears appropriate. However, perhaps there is an indication here of the rudimentary difference between what forms are appropriate, what forms are adapted, and how either form respects the nature of materials.

Nervi states that the fundamental requirements of construction are functional, economical and aesthetic.[29] The following sections deal with each of these three qualities in turn. This section deals with how these requirements translate into form. Nervi writes,

> All [the] promising developments [of reinforced concrete structures] are made possible by the progressive liberation of reinforced concrete from the fetters of wooden forms. Until these bonds are totally removed, the architecture of concrete structures is bound to be, even if briefly, an architecture of wooden planks.[30]
>
> Reinforced concrete beams lose the rigidity of wooden beams or of metal shapes and ask to be molded according to the line of the bending moments and the shearing stress.[31]

It can be assumed that the *functional* requirement of the beam stays the same whether it is rigidly shaped or molded. The *economical* requirement is addressed by the amount of material necessary for the structure, and the labor and material needed for construction. To economically build floor slabs with ribs that follow the isostatic stress lines of the structure, such as that at the Gatti wool plant in Rome, Nervi had to fabricate special forms that could be used repetitively. (**Fig. 5.7**) Supplementary finish work, such as plastering, was unnecessary because the formwork was fabricated with high finish quality.[32] Therefore, both

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[29] Nervi^2, p2.
[30] Nervi^2, p101.
[31] Nervi^1, p22.
[32] Nervi^2, p101.

the construction process and finish work had to be considered to keep the cost of the system competitive with more conventional 'rigid' forms with rectilinear ribs. Finally, what are the aesthetic qualities of Nervi's slab? Beyond creating a visually dynamic pattern, this form explicitly expresses the flow of forces through the structure. The curved ribs and the monolithic form of the structure express that the material is made plastically, and that it can be made into seamless, complex forms. The thickness of this floor indicates that the material can be stressed in tension. The span and thickness of the slab give us an appreciation for the material's strength. The ribs visually express a stiff structure. Therefore, this floor slab visually expresses the physical nature of the material as defined above. By looking at this structure, we can learn about the essential qualities of the material used to build it. Viollet-le-Duc verbalized this approach to design when he wrote,

> Let it be well understood, once for all, that architecture cannot array itself in new forms unless it seeks them in the rigorous applications of novel methods of construction; that casing cast-iron columns with cylinders of brick or coatings of stucco, or building iron supports into masonry, for example, is not the result either of calculation or of an effort of imagination, but merely disguising of the actual construction; no disguise of the means employed can lead to new forms.[33]

We can conclude that *building 'correctly' means not only using materials in accordance with their nature, but also expressing that nature explicitly in the form used*.

What if a material is not expressed in such a way? What if a slab with rectilinear ribs is built? Is its form 'incorrect'? Is its form inappropriate? Does this form go against the material's nature? I will use the example of Coop Himmelb(l)au's Funderwerk, in Kärnten, Austria, to examine these questions. (**Fig. 5.2**)

The structural design for the Funderwerk building is an irrational system. The lines of structure were determined before there was a structural concept. However, it works; the criteria for saying so simply being that it exists and has not failed. Just because the system is not rational, does that make the form 'incorrect'? This structure does not exhibit Gestalt qualities, though this is an admittedly subjective judgment. It does not express the same clarity of purpose, function and materiality that Nervi's floor does. The fact remains that the structure of the Funderwerk works.

Nervi recited a story about the Risorgimento Bridge in Rome that was calculated by German engineers to fail though the bridge was standing. (**Appendix A-06, p.A.274, Fig. 7**) The theory said it was wrong.[34] However, this daring structure was sound and proved to be an efficient form. Its deck-stiffened, box-section arch makes the slenderness of this bridge possible. Coop Himmbelb(l)au designs 'it is what it is' architecture, however, it cannot be concluded that the material is used wrongly. The fundamental nature of the material is respected because it can be processed and is subject to stresses within its capacity. *If it were wrong or incorrect, it would either fail or not be producible at all*.

This section has concluded that the nature of a material is a product of its material properties and its processing and constructive attributes. Any form that respects these basic qualities

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[33] Viollet-le-Duc^2, p65.
[34] Nervi^2, p15.

has to be considered an appropriate use of material. However, material-adapted form is not only an appropriate use of material, it is a *good* use of material. The objective now is to identify what qualities a form needs to make *good* use of a material. These qualities will become part of the Gestalt concept of material-adapted structural form.

5.4 Characteristics of Good Structure

5.4.1 Function + ?

The first qualification of a good structure is that it satisfies the programmatic, structural and non-structural requirements described in **Section 4.2**. The Function Pattern defines the spatial limits within and without that a structure can occupy. The designer's choice of structural systems and forms is restricted by these spatial limits.

That *structure must fulfill its functional purpose* is obvious and comprises part of a structure's Gestalt-quality. This quality eliminates arbitrary or frivolous structural forms from consideration as what constitutes good structure. However, it is not sufficient to classify a structure as good simply because it meets these requirements. The remaining qualities are what David P. Billington, a professor and historian of structural engineering at Princeton University, defines as efficiency, economy and elegance. Billington calls these three qualities the "ideals of structural art."[35]

Nervi wrote, "The structure, be it large or small, must be stable and lasting, must satisfy the needs for which it was built, and must achieve the maximum result with the minimum means."[36] It can be concluded that *good structure exhibits the same Gestalt-qualities irrespective of scale*. *Efficiency* and *economy* are two integral components of the Gestalt-quality of good structure. Nervi indicates that there is a balance to be struck between the maximum result, defined by efficiency, and the minimum means, defined as economy. Efficiency and economy are not necessarily complimentary and the term 'efficiency' needs to be further examined. The following sub-sections examine these qualities, as well as Billington's quality of elegance, which is another way to define the *aesthetic quality* of form.

5.4.2 Efficiency + Economy = Optimization

There are two levels of efficiency. The first is *structural* efficiency. Reference to the efficiency of engineering structures most often refers to this level of efficiency. Efficiency can be redefined if we look at the building system as a whole. **Section 5.4.3** examines this second level of efficiency.

Structural efficiency is achieved by minimizing the amount of material necessary to satisfy a particular structural function. Efficiency is primarily a function of System and Component level geometry, and a material's strength and stiffness properties. These properties determine whether a structure will maintain its form within a defined tolerance of space as set by the function pattern and performance criteria that limit deflection of the structure. These tolerances vary depending on the programmatic function the structure is supporting. The

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[35] Billington, p267 and 269.
[36] Nervi^1, p2.

deflection of a long-span pneumatic roof over a tennis court is not as critical as it is for a railroad bridge.

The analysis of efficiency has to take into account the function pattern and the programmatic requirements the structure serves. The most efficient structures are subject to axial tension, such as suspension bridges. However, such a structure is not practical for making the floors of multi-story buildings. It is necessary to use structural components such as beams that, if examined in isolation from the System and functional requirements, are not the most efficient way to transfer load. The beam is superior to suspension systems as a floor-supporting Component in a multi-story building System because it minimizes the depth of the structure.

Structural efficiency is not always the most important consideration when using a material. The Greeks had a limited selection of materials to choose from to build their temples. Stone and wood were the only viable structural materials available. The Greeks chose to use stone because it best addressed their desire for a material that was durable. Additionally, the sculpture that was an integral part of Greek architecture could be carved directly into the structural material. Timber required that a separate material, like terracotta, be sculpted and applied to the façade, which complicates construction of the building system.[37] (**Appendix A-01, p.A.4, Figs. 3 and 4**) The form of the bulb-tee beam is another example in which non-structural requirements influence form. (**Appendix A-03, p.A.99, Fig. 29**) The bulb-tee beam was shaped to facilitate the inspection and maintenance of cast-iron deck beams in ships.[38] Therefore, we can conclude that *functional requirements are not always conducive to achieving structural efficiency, but loss of efficiency is acceptable if non-structural requirements are better served*.

Structural efficiency has to be considered on three levels delineated by the hierarchy of structural form defined in **Chapter 03** – System Form, Component Form, and Element Form. The efficiency of System Form is largely determined by geometry, and the Function and Load Patterns. The nature of a material will determine what System Forms are most amenable to the particular properties of a given material, but the form itself depends most on statics and the Function Pattern.

Component Form is a combination of geometry, statics and material properties. The efficiency of Component Form cannot be addressed until the System Form has been defined because functional requirements determine what space structure may occupy. If structure is defined by immaterial lines projected on a drawing, as is done by Coop Himmelb(l)au, then the structure must conform to a System Form that was not conceived with System efficiency in mind. (**Fig. 5.2**) Efficiency can be gained on the Component and Element Levels by using the best forms for the given situation in such a design.

The Element Form of composite materials is determined by the internal stresses of a Component and the nature of the constituent materials. The flat slab designs of C.A.P. Turner and Robert Maillart, examined in **Appendix A-05**, are examples of how such forms can be counter-intuitive. (**Appendix A-05, p.A.255, Fig. 34 and p.A.261, Fig. 39**) Turner's design orientates the steel reinforcement in multiple directions to explicitly reflect what he understood to be the principle stress lines in the slab. Maillart's design is based on a

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[37] **Ref. Appendix A-01, p.A.4-A.9**.

[38] **Ref. Appendix A-03, p.A.99-A.100**.

uniform, orthogonal grid. Maillart realized that the component forces of the structure did not have to be addressed by any one direction of reinforcement. The stresses could be transferred as component forces through the bi-directional arrangement of iron. Maillart's design exhibits the qualities of efficiency and economy, as well as constructive simplicity.

A note on the Detail form should be briefly considered before continuing with an examination of the relationship between efficiency and economy. While it is true that Components subject to axial tension are the most efficient, these components require relatively heavy end fittings to transfer the forces to the anchorage points. Furthermore, such structures demand special foundation conditions because they transmit horizontal component forces like form active structures under compression. This is not the case with section active structures such as beams in which the stresses are restrained internally. Such details can change the relative efficiency, and cost, of a structure. As a rule, tensile structures become more efficient and economical the bigger they are.[39]

Economy is a function of material use, processing and constructive complexity, and socio-political factors. Structural efficiency and economy are not necessarily complimentary. Increased efficiency often increases structural, processing, and constructive complexity. Complex structures require more design time. Complex structural forms, such as the cast-steel gerberettes used in the Pompidou Center require special processing. (**Figs. 4.23 and 5.5**) Tensegrity structures, which are highly efficient, are constructively complex because the System is unstable until all of the cables are tensioned properly. Such issues present a trade-off between economy and efficiency. Therefore, structural efficiency is an ideal, but not always economical. If the conflict is technological, such as the limits of processing technologies, then there is the possibility that efficient forms will not remain uneconomical. The developer of materials should bear this in mind when considering to abandon a particularly efficient form that is uneconomical. The developer can work towards improving or inventing methods for producing the desired form economically.

One way to balance the often-competing objectives of efficiency and economy is optimization. Optimization in engineering is too often confused with the search for maximum structural efficiency. This can be one useful goal, but it is not the sole definition of optimization. Douglas Wilde, author of a book on the origins and definition of optimal design[40], defines optimal design as "the best feasible design according to a pre-selected quantitative measure of effectiveness."[41] In structural engineering, the quantitative measure of effectiveness can consider the cost in addition to physical parameters. Therefore, *good structure must reflect a balance between efficiency and economy, though the goal should be to make this relationship complimentary*. *Efficiency and economy are reconciled by optimization when they are not complimentary.*

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[39] Gordon[1], p304-307.

[40] Wilde, Douglas and Charles S. Beightler. *Foundations of optimization*. Prentice-Hall, Englewood Cliffs, New Jersey USA. 1967.

[41] Paraphrased in Haftka and Kamat, p1.

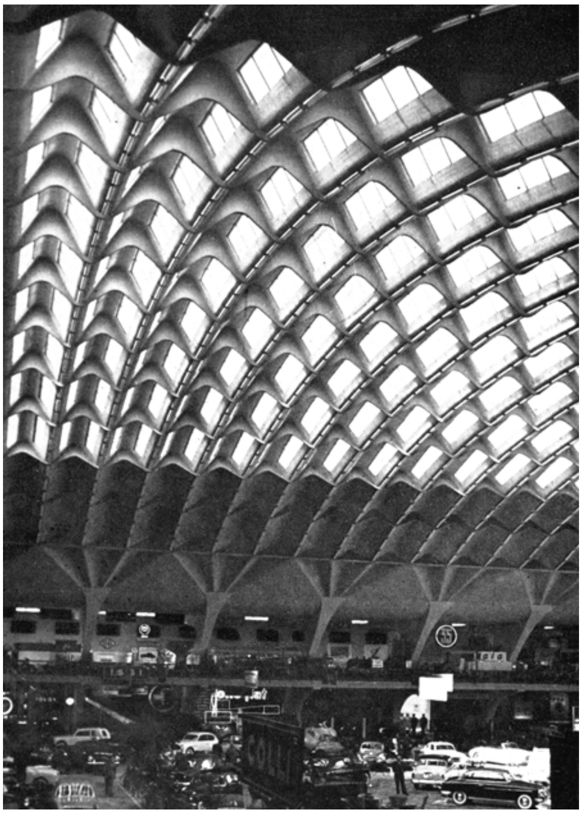

Fig. 5.8: Turin exposition hall. The vault is made from prefabricated ferro-cement segments 4.5 m long. Pier Luigi Nervi, 1947. (Desideri et al.)

5.4.3 Function integration + Economy = Efficiency

Function integration is an aspect of structural form that Nervi, Viollet-le-Duc, and others fail to consider explicitly when speaking of efficiency and economy. Nervi considers efficiency as two separate phases of architectural achievement:

- Creative efficiency, which decides the principal characteristics of the work
- The efficiency of its realization, which defines dimensions and structural characteristics in detail, and governs the economic and administrative relations with the contractor.

Nervi writes, "The first phase is obviously more important. The strictest economy of execution will never compensate for a poor plan or a mistaken structural solution."[42] Therefore, Nervi emphasizes that *structural efficiency* must be the starting point towards making efficiency and economy compatible. If the search for efficiency is abandoned for strict arguments of economy, then Nervi implies that it will probably follow that the most economical structure will not be had. This is consistent with the form-finding model presented at the end of **Chapter 04**, in which Ideal Form is conceived of in two phases. The first seeks the most efficient structural solution. The second integrates material properties into the system to determine the minimum mass necessary to address the structural requirements of the structure.

Nervi's structures exhibit a quality that indicates Nervi has perfectly integrated the economy of processing and construction with structural efficiency. However, his writings fail to address how efficiency can be gained by function integration. This is surprising because Nervi had to deal with function integration problems such as structures that act as environmental barriers and incorporate apertures allow natural light to enter the building. (**Fig. 5.8**)

Heinz Isler, a Swiss engineer known for his free-form shells, reduced the cost of constructing such structures by using the formwork as insulation in the finished building. Isler reduced the cost of falsework, typically 50% the cost of a shell, to only 20 to 25% of the cost, in part by using the permanent formwork.[43] Therefore, Nervi's "minimal means" can also refer to the economy of processing and construction.

Material efficiency can be measured by considering the building system as a whole as Isler did when using the formwork for different purposes during construction and when the building

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[42] Nervi^2, p7.
[43] Chilton, p19.

was in-service. This type of function integration thinking is an important component of how the subjects of efficiency and economy are addressed. Combining structure with secondary structures or non-structural functions can offset the increased cost of structural efficiency

The case of the tapered beam illustrated at the end of **Chapter 04** in **Model$_1$** gives a good example of how Nervi's statement is deficient for not including function integration. The use of the tapered beam in the Embankment Place Building shown in **Figure 4.37**, demonstrates the complexity of economy. The tapered beam is not typically economical for the standard steel framed building because of the additional processing costs to make such a form. In this case, the designers wanted to squeeze another floor within a strictly limited building-height limit. Their solution was to integrate the design of the beam with the mechanical and service systems of the building, an example of complementary integration. This example demonstrates the economic benefits of increasing the cost of the structure in order to achieve economy elsewhere. In this case, the economy was achieved by increasing the useable floor area of the building. The increased cost of the floor structure was an investment that would be recouped through increased space that can be used to generate revenue. Concerning the form of the beam, a balance was struck between the efficiency and economy of the Component. The most efficient form of the beam would have been if the lower flange were curved to precisely follow the moment diagram. The Implemented Form is linearly tapered. This form is cheaper to make than one with a curved flange. Its shape is preferable to a curved flanged because the straight angle simplifies any connections needed to hang pipes and other service equipment from the beam.

The design for an Antarctic Research station illustrated in **Figure 4.6** provides an example of integral integration and how efficiency can be viewed more holistically than when limited to structural efficiency. The exterior building panels of this building act as both structure and environmental envelope. The building panels are comprised of FRP sandwich Components. The sandwich material doubles as both structural stiffener and thermal insulation. In this case, the structural efficiency was not compromised and further efficiency was achieved by part-count reduction, which decreases constructive complexity and simplifies maintenance.

These two integration examples show that total building efficiency can be achieved without sacrificing structural efficiency. On the contrary, they encouraged efficiency. Any economical penalty for this efficiency is offset by reducing the need for secondary materials, as such would be the case if the Antarctic Station were built using a more conventional frame system whereby the environmental envelope was applied to it. *The objective of function integration is to achieve a net reduction of material in the building system. Increased processing complexity should be offset by decreased constructive complexity, part-count reduction and reduced maintenance requirements*.

5.4.4 Aesthetics

A discussion of what constitutes good structure would not be complete without addressing aesthetics. This thesis has purposely avoided the subject of aesthetics because of its subjective nature. However, the best structures are not only beautiful, but also exhibit a link between the visible and physical qualities of what constitutes good form. The writings of Viollet-le-Duc and Nervi recorded in **Section 5.3** alluded to this link. It is appropriate that aesthetics is briefly considered here.

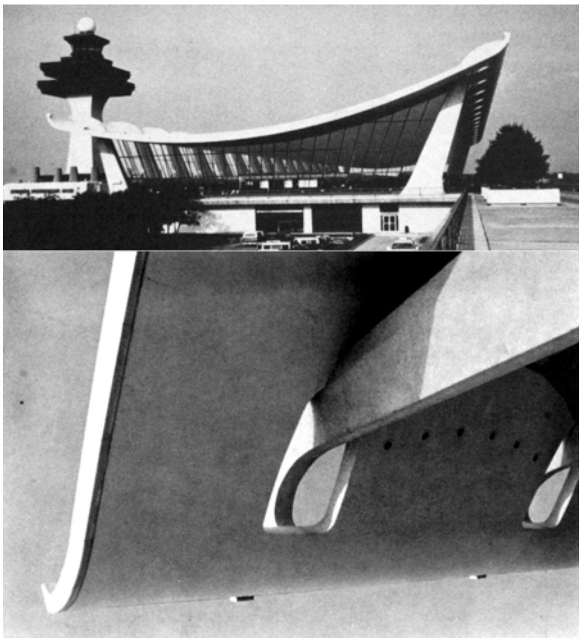

Fig. 5.9: General view and detail of cable suspended concrete roof of Dulles International Airport, Washigton, D.C., Eero Saaranin, architect, Boyd G. Anderson, engineer. 1965. (Zannos)

There is a consensus among Nervi, Viollet-le-Duc and Torroja that the tactile aspects of static function, efficiency and economy are intrinsic aspects of aesthetically good structural form. Nervi's slab design for the Gatti wool factory reflects this quality. (**Fig. 5.7**) Aldo Arcangeli, one of the engineers in the design office of Nervi and Bartoli, suggested that the ribs of a slab should follow the isostatic stress lines that are determined by the principal bending moments in the slab. Nervi writes, "These lines depend exclusively on the loading conditions of the structure, and it was amazing to find that by thus limiting our task to the interpretation of a purely physical phenomenon, we were able to discover unexpected and expressive new forms."[44] Nervi makes a direct connection between aesthetic beauty and the apparent expression of static function. This is also expressed also in his Risorgimento Bridge in Verona. (**Fig. 4.11**)

Jean-Nicolas-Louis Durand, professor of architecture at the Ecole Polytechnique in Paris between 1795 and 1830, supported the tenet that economy is a factor in aesthetic beauty. He wrote: "In creating architecture it is fallacious to assume that beauty and economy are incompatible, or even merely compatible, for the latter is one of the principal causes of the former."[45] This supports the view that that forms should express structure honestly, and that structure should be economical and efficient. From Viollet-le-Duc, Nervi, Wright and others we also know that this structural aesthetic should express the nature of the material as defined in **Section 5.3**.

There is a limit to which this structural honesty can be treated without confronting the metaphysical and symbolic meaning of form. Alexander Zannos, author of the book *Form and Structure in Architecture: The Role of Statical Function*, cites the example of the Dulles International Airport Terminal near Washington, DC, as an example of where the expression of structure can affect the efficiency of structure. (**Fig. 5.9**) Zannos calls this "the complementary and antithetical relation between the "logic" of a technical form and the "irrational" aspects of an art form.[46] A long-span, cable-supported reinforced concrete roof characterizes the Dulles Terminal, designed by the architect Eero Saarinen and the engineer Boyd G. Anderson in 1965. Distinctive, outward-leaning masts support this roof, which means that the longitudinal edge of the stressed ribbon must act as a transfer beam. Structurally, it would have been most efficient to have a solid, monolithic connection between

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[44] Nervi^2, p101.

[45] from Durand, *Précis des léçons d'architecture donnée à l'École Polytechnique*, I, 2, 3. from volume 1, p20, copied in De Zurko, p171.

[46] Zannos, p311-312.

the roof and the supports. This probably would have been more economical to build as well. Saarinen designed this interface with an opening that the mast penetrates to emphasize the tension between the two structural components. The visual effect successfully emphasizes the static function of the structure. This example shows that there is a place in the design of structures for more subjective choices of form than just what is required structurally.

Many of the best ‘structural artists’ were intimately involved in both design and construction of their structures. Thomas Telford, Gustave Eiffel, Robert Maillart[47], Pier Luigi Nervi and Felix Candela all provided design and construction services. Candela stated, “The only way to be an artist in this difficult specialty of building is to be your own contractor.”[48] Perhaps this is a characteristic of successful developers of material-adapted form.

5.4.5 Good Structure

This section has demonstrated that good structure is characterized by the following characteristics:

- A good structure must first satisfy functional requirements.
- A good structure seeks to balance efficiency and economy by respecting a material’s nature as it is defined in **Section 5.3**.
- A good structure should seek to reduce constructional complexity and increase the efficiency of the total building system where possible. This is achieved by function integration, which was defined in **Section 4.2.6** to be either integral or complimentary. The objective should be to achieve a net reduction of material and constructive complexity for the potential increase of design time, structural material quality and processing complexity.
- The qualities of good structure should be expressed aesthetically. The designer must use discretion whether, and how much, to accent these qualities visually at the expense of efficiency and economy. Any additional expense should be minimized.

5.5 Defining Material-Adapted Structural Form

5.5.1 Summary of the Aspects of Material-Adapted Structural Form

This thesis started with the hypothesis that *material-adapted structural form is not unilaterally determined by a material’s structural properties*. The preceding sections of this chapter have shown that *material-adapted structural form is a combination of a material’s nature and several criteria that constitute good structure*. Collectively, these properties, attributes and criteria constitute the Gestalt-quality of structural form. The aspects of the Gestalt-quality are summarized below after a review of the conclusions made in **Sections 5.2 to 5.4**. Structural forms that exhibit all of these aspects are here considered to be material-adapted.

Section 5.2 concluded that structural form has both metaphysical and mechanical limits. The metaphysical limits are defined by a designer’s ability to conceive of form. Form is the

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[47] Maillart did not continue to manage his own construction company in the second half of his career.
[48] Billington, p210.

conceptual product of our imagination. Mechanical limits are defined by both a particular material's mechanical properties, and the limits of the technology used to actually shape or process material into form. Form can be conceived of without the material available to realize it. This means Constructible Form is limited by the availability of materials. Finally, structural form is not defined by its outward appearance, but has a Gestalt-quality. This is to say, form is not an entity without there also being other qualities such as the properties of the material it is made from, how the material was processed and holds the shape of the form, and the function it serves.

Section 5.3 defined the *nature* of a material as characterized by the material's properties (both structural and non-structural), and the material's processing and constructive attributes. Material properties are absolute, however our knowledge of them is not. Processing and constructive attributes are non-absolute. These attributes change with knowledge and ideas about form, and the technology to make it. Therefore, the nature of a material is not a static concept because of the non-absolute qualities of its definition. Restrictive lists that attempt to identify forms that are particularly suitable to a material should be avoided for this reason. If such lists are used as a design tool then they should be periodically checked to control that the premises they are based on remain valid.

Section 5.3 addressed the question of what *materially appropriate* form is. Appropriate form simply implies that a form respects the nature of a material, otherwise the material would fail or the form would not be producible in that material. Material-adapted Implemented Form best exploits and expresses these properties in addition to striving for material efficiency, building economy, and aesthetic beauty. The designer must recognize that processing and construction properties are part of a material's unique combination of properties. The designer must also distinguish between the properties and attributes of the material in all three phases of processing, construction and in-service. A materials disassembly and recycling attributes could be added to this list. This thesis has not discussed these attributes in detail but they deserve further study because of their importance to analyzing life-cycle costs and addressing issues of sustainable development.

The final form of a structure is a combination of static function and the nature of a material. The difference is highlighted by the materially appropriate cross-section of Eaton Hodgkinson's 'ideal' cast-iron beam and the structurally appropriate longitudinal section of a tapered beam. (**Model[1], p104 and 106, Examples 2 and 5**) The 'ideal' longitudinal section would have a curved bottom flange with the maximum depth at mid-span. These material and non-material parameters of structural form are reconciled, or jointly considered, by the efficiency of the structure.

Relatedly, the concept of material-adapted form has to take into account *both* structural and non-structural aspects of material usage. A good structure first satisfies the functional requirements. By this standard, the use of stone beams in Greek antiquity should be considered an adapted use of the material because it not only satisfied the structural requirements, but also provided the durability that was of particular importance to the builders.

Section 5.4 mainly considered the question of what makes form good. The difference between *appropriate form* and *good form* is distinguished by what is *possible* versus what is *preferable*. The first tenet of good structure is that it satisfies the functional purpose it is designed to serve. Good structure reconciles the possible conflict of efficiency and economy through optimization, though it should be the intention of the designer to make efficiency and economy complimentary to each other. Efficiency can be limited to structural efficiency, or it can be redefined to consider the efficiency of the whole building system through function integration. The objective of function integration is to have a net efficiency of material and net economy for the building system as a whole even though some lost efficiency and/or economy of the structure might have to be accepted. It should be the designer's intention to maintain or improve structural efficiency and economy through function integration. Function integration helps to reduce the part-count and constructive complexity of the building system. Finally, good structure has aesthetic beauty that expresses the nature of the materials used and the aspects that make it good structure.

Economy and optimization are important aspects that must be integrated into a definition of material-adapted structural form in order that such forms reach the Implemented phase of form-finding. However, the Gestalt-quality of this definition leaves open the identification of Ideal and Constructible Forms that can be addressed individually to improve processing technologies or the technics of building such that Ideal or uneconomical Constructible forms become economical. Function integration, or just the idea of function integration, can be an integral tool in this process. The integration of the airframe and the aerodynamic envelope of airplanes to create monocoque and stressed skin structures is a salutary example of how powerful this concept is.

Material-adapted should be distinguished from best-fit applications. Material-adapted forms exploit a material's nature to the fullest extent possible. Best-fit applications are those where a material is chosen by suitability criteria determined for a given application and form. Such applications match an application with a material that simply satisfies the requirements of the particular application better than other materials. Further design or analysis would have to be done to determine if the application is adapted or not.

5.5.2 A Definition of Material-Adapted Structural Form

Material-adapted structural form is defined as structural form that exhibits all aspects of the Gestalt-quality. The aspects of the Gestalt-quality of structural form are:

- Structural form has metaphysical and mechanical limits.
- Structural form has limits related to the availability of materials, material properties, and the ability to process and build with those materials.
- Form: structurally appropriate vs. materially appropriate. Link is Efficiency!
- Structural form exhibits the inherent characteristics of the process by which it was made.
- Structural form must respect and visually express the nature of the material it is made from.
- Structure should be efficient and economical. Efficiency is defined by structure alone or by the whole building system using function integration. Economy is related to material, processing, construction, and design costs, as well as socio-political factors.

These aspects are addressed by optimization. The goal is to make economy and efficiency complimentary, such that economy does not limit the implementation of material-adapted form.

- Finally, all of these qualities should be embodied and expressed visually in the outward appearance of the structure.

These aspects are summarized in a statement by John Ruskin, an English writer, artist and philosopher of the nineteenth century. Ruskin wrote, “Materials should be used in a manner that respects their natural properties, laws, virtues, and limitations.[49] Ruskin’s description of how materials should be used is a more precise definition of the nature of materials and material-adapted form than offered by any of the aforementioned architects and engineers in this chapter.

Because the nature of a material is non-absolute, the concept of material-adapted form is also subject to change. Philosophically, this concept is explained by Plato’s view that ideas are pure forms, and the world manifests forms in the process of being realized. The developer of materials can interpret this to mean that structural forms are never going to reach a state of perfection, but the objective is to strive for it by understanding the Gestalt-quality of a material and letting it inform the form-finding process.

A concise definition of material-adapted form is:

Material-adapted structural form respects the nature of a material, is optimized for efficiency and economy, and aesthetically expresses these qualities.

Ideally, material-adapted form will not be limited by economic factors; rather its efficiency will be complimentary.

5.6 Some Notes on Substitution

5.6.1 The Substitution Phase of Material Development

Now that the meaning of material-adapted form is defined, it is appropriate to reconsider the hypothesis that each new structural material must transcend a substitution phase before material-adapted forms are developed. This hypothesis is based on the supposition that first-use forms are substitutional. Typical examples of such first-use forms are: the stone beam in Greek antiquity; the arch form of Ironbridge in England in 1779; the use of cast-iron voussoir blocks in other cast-iron arches; and the reinforced concrete beam-slab floor construction Hennebique System employed around the turn of the twentieth century. This last example is commonly mistaken to be a first-use application.

Pier Luigi Nervi believed that reinforced concrete was used substitutionally until the development of the flat slab in the first decade of the twentieth century. Nervi wrote,

> [Reinforced concrete] frees our structural imagination almost completely, and it is sad to realize that so far its potentialities have been little explored and even less used. In all technical fields, including construction, there is a strange tendency to use old schemes in connection with new processes or new

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[49] De Zurko , p135-136.

> materials, which, if applied in complete freedom, would allow substantially better results.
>
> Generally, reinforced concrete has been reduced to the forms and structural shapes typical of steel or masonry, neglecting most of its many possibilities and specific characteristics. The characteristic property of a reinforced concrete structure is its monolithicity, and from it may be derived some of its most brilliant static solutions.[50]

Nervi's view is a standard interpretation of the use of reinforced concrete until the turn of the twentieth century. However, it ignores the early developments of reinforced concrete that used this material in complex, new forms. Joseph Lambot and Joseph Monier's flowerpots, designed to hold orange trees, take full advantage of concrete's plasticity, strength, and ability to contain liquids. These pots had to resist hoop stresses introduced by the pressure of the plant roots inside.[51] Historians of reinforced concrete generally under-appreciate the size of these flowerpots, the structural load they were subject to by the force of the roots and, possibly, freeze thaw effects.[52] Joseph Lambot's ferro-cement boat is a prime example of how the pioneers of reinforced concrete understood the potential of the material. Lambot's boat is generally relegated as a footnote to the early development of reinforced concrete. It is hardly recognized as one of the first reinforced concrete thin shell structures.[53] (**Appendix A-05, p.A.238, Fig.4**) Historians have not adequately explained why this boat did not lead to the development of reinforced concrete thin shells sooner. Other early applications of reinforced concrete, such as its use in water towers, of which the flowerpots are antecedents, and the slender

Fig. 5.10: Reinforced concrete water tower, Monier System. Joseph Monier, c.1876. (Bosc)

Fig. 5.11: View of Hennebique reinforced concrete construction system. Warehouse in Nantes, France. Clériceau and Tessier, architects, 1903. (Delhumeau et al.)

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[50] Nervi^2, p29-30.
[51] **Ref. Appendix A-05, p.A.238-A.239**.
[52] Bosc, Huberti, Newby.
[53] *ibid*.

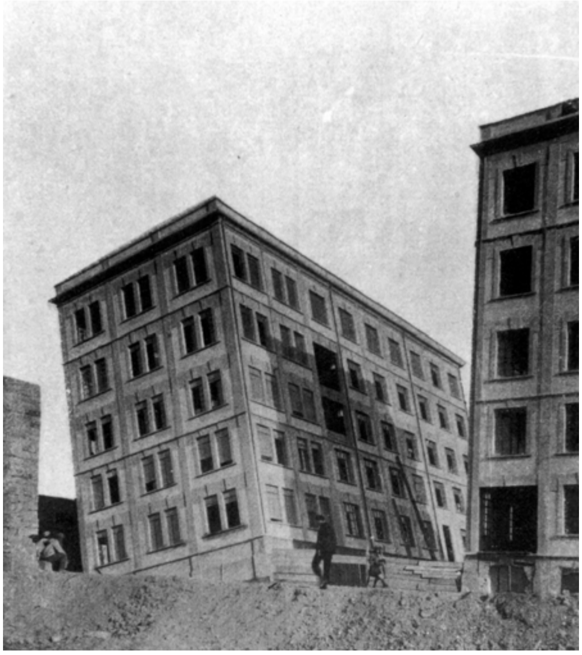

Fig. 5.12: Uneven settlement of building demonstates monolithic strength of the Hennebique reinfoced concrete constructiton system. Mill building, Tunisia, 1906. (Delhumeau et al.)

arches of the German Monier System licensee Wayss & Freytag both aptly demonstrate that reinforced concrete was not simply substituted for other materials. (**Fig. 5.10; Appendix A-06, p.A.240, Fig. 8 and p.A.241, Fig. 9.**)

The reinforced concrete structures Nervi is referring to are specifically building structures, exemplified by the Hennebique System. (**Fig. 5.11**) Nervi thought that the beam slab system was in some way inappropriate and that those who used these forms did not understand the nature of reinforced concrete. He wrote,

> A concrete beam with participating slab reproduces in its exterior form the old wood-beam floor, but differs substantially from it because of its monolithicity. For example, the old beam-floor system can resist only vertical loads, since each of its elements works independently. The modern beam-slab system, on the other hand, may also resist horizontal loads (even if this fact is often forgotten). Similarly, each beam is rigidly connected with the column on which it rests, every frame constitutes a unique structure in which the stresses of one element are felt in all the others, and loads are distributed to the whole resisting organism.[54]

Nervi's charge of substitution does not hold up to scrutiny. As he points out, the connections of the reinforced concrete beam-slab system are monolithic. This quality is expressed in Hennebique's system at the beam-column interface where the beam flares out at the connection. This form demonstrates that such a connection is moment resisting and accounts for the negative moment of a continuous beam over an interior column. Nervi claims that designers of the beam-slab system do not recognize the floor's capacity to resist horizontal loads. I do not know whether Hennebique capitalized on this fact, but he did recognize its existence. Hennebique not only understood the monolithic quality of reinforced concrete, he actively marketed that quality. The tilting building shown in **Figure 5.12** was published in Hennebique's in-house journal, *Le Béton Armé*, as an example of the monolithic qualities of reinforced concrete.

It is hard to conclude that the beam-slab floor system is strictly a substitutional application of reinforced concrete. Substitution implies that a material's nature is not understood. Based on the definition of the nature of a material, the beam slab has to be at least accepted as an

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[54] Nervi^2, p30.

appropriate use of material. The question then is not one of correctness or substitution, but of efficiency.

The early development of reinforced concrete demonstrates that the early pioneers well appreciated the nature of the material they were working with. In fact, the first applications of the material can be classified as material-adapted. The beam-slab system is an appropriate use of material but can be criticized for not making the most efficient use of material. The system form of the beam slab can be considered an adaptation of a material to the System Form of another, though the label of substitution cannot be justified when the details and method of construction were clearly adapted to the material. I have not found a single instance where the beams and columns were connected mechanically in the fashion of steel or timber construction that shows that the nature of the material was not understood. There is no apparent explanation why the flat slab was not invented in the same period early reinforced concrete arches were constructed of thin, curved plates. Perhaps there is another explanation, because it cannot be concluded that material-adapted forms had not already been developed by the time that the beam-slab became the dominant mode of reinforced concrete construction.

5.6.2 The Place for Substitution in Material Development

In the later half of the nineteenth century, Eugène-Emmanuel Viollet-le-Duc was interested in adapting architecture and structural form to iron. Viollet-le-Duc explained the design community's reluctance to use iron as follows:

> It would seem as if our architects were ashamed to employ iron; they conceal it as far as possible beneath plastering and pugging, which give it the appearance of a masonry structure.
>
> We are familiar with the simple and natural methods by which the mediaeval architects of our own country counter-thrusted their vaulting, – namely, by buttresses and even flying buttresses, that is by exterior resistance, inert or acting obliquely. In Italy, architects adopted a more simple contrivance; they placed horizontal iron tie-bars above the springing of the arches at the line of thrust. In point of fact, the thrust of vaulting must be resisted either by abutments or by ties, to obviate the spread. How is it that while in France we object to the appearance of interior ties beneath our masonry vaulting, our sight is not offended by the presence of those which are so profusely employed in Italian buildings?
>
> The use of iron allows of [sic] feats of construction from which we seem to shrink back. It would appear that we have only an imperfect confidence in the properties of this material. We employ it only as a means of producing additional security, i.e. with reservations so that instead of lessening it often serves only to increase the expense.[55]

Viollet-le-Duc illustrates two important aspects of the introduction of materials to the building market. The first aspect is cultural. New materials challenge established aesthetic precepts. Time has to be given to allow the design profession to assimilate a new material, or rather, the market has to adapt to the material. The second aspect is characterized by the practical

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[55] Viollet-le-Duc^2, p66-67.

matters of knowledge and experience. Though engineers had worked with iron for over half a century before Viollet-le-Duc wrote the above passages, architects had limited experience with material. They did not understand its nature; they did not know how it would behave. Using the material in known forms of known materials allows the designer to easily compare the particular qualities of a new material. Therefore, substitution can be a useful, even necessary, phase in the development of material to allow designers and builders to learn how the material behaves and what its nature is. Importantly, clients may be willing to try a new material more readily if at least the form does not greatly challenge their expectations of what a structure ought to look like. It should be recognized, as demonstrated by the example of reinforced concrete, that the use of substitution does not necessarily mean that adapted forms have not already been identified. The chronologies of material evolution annexed in **Appendix A-09** support the hypothesis that new materials are indeed used in adapted ways from the beginning. It can be argued that the substitution phase of development comes after the pioneering users of a material succeed in establishing the material as safe and capable for general use. Once the use of the material moves out of the hands of the original devotees and into general use, there is a learning curve that must be effected. Designers, builders, and especially clients, need to learn about the material in a manner that they will not perceive as too risky. Though the pioneers are confident in the material, new users must gain the same confidence. That confidence can only be got by experience.

5.6.3 New Material, New Form?

The idea of substitution raises the question of whether the forms established materials are being substituted for by a new material are actually adapted to the original material. According to Frank Lloyd Wright, “Every new material means a new form, a new use if used according to its nature.”[56] Is this necessarily true?

The stone beam of antiquity is interpreted as case of substitution for timber construction in a number of texts.[57] As shown in the last section, the use of stone as a beam in Greek antiquity meets the requirements of material-adapted form. It is important to consider that the Greek’s decision to use stone was taken in the context of material availability and knowledge at the time. It was a cultural imperative that the temples be durable and last, at least figuratively, for eternity. This was a functional requirement that timber could not meet. Furthermore, stone was also amenable to integrating the structure with the architectural ornament of the aesthetic language used for design. In accordance with the definition of material-adapted form, loss of structural efficiency can be balanced by efficiency of the building system. The sculptural ornament of Greek architecture could be carved directly into the structural material. This resulted in the favorable quality of part-count reduction that reduces constructive complexity. When using timber, the Greeks manufactured this ornament in terra cotta and then applied it to the structural system. (**Appendix A-01, p.A.4, Fig. 3**) The terra cotta additionally protected the wood. I do not know whether this was its primary or secondary function. In any case, all three requirements – structural, durability, and aesthetic, could be satisfied by one material, stone.

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[56] Wright, p198.

[57] Dinsmoor; Coulton; Viollet-le-Duc[1]. **Ref. Appendix A-01**.

Stone was appropriate and adapted to the application *and* context. However, the nature of a material is not a static concept. Just as its meaning can be used contextually to justify using stone as a beam, it does not follow that this can be considered an adapted use when the Greeks became aware of the arch. Perhaps they did not understand the efficiency of this structural form. Indeed, the limited use the Greeks made of the arch indicates that they did not appreciate this structural form's potential at all.[58] In any case, the use of stone in lieu of wood seems to be an example of Plato's definition of form. In this case, wood was first used to model true form, and stone did it better. Is there any material today that could last as long as the stone beams still to be found in Greek ruins?

Ironbridge, built in England in 1779, is another example of what could be interpreted as a case of substitution. (**Appendix A-02, p.A.14, Fig. 17**) Ironbridge has a semi-circular form characteristic of a stone arch and connections that are wedged and pinned like timber construction. The connections have to be seen in the context of processing technology and inexperience building such structures. (**Fig. 3.10, top-center**) The wedged connections are actually adapted to the material because they distribute the stress more evenly over the components being connected than a bolt would. Such a connection is good for cast iron because cast iron has a low resistance to fracture. A bolted or pinned connection would require putting a hole in the component that creates a high stress concentration. Criticism of the arched System Form is not supportable. This is cast iron, not wrought iron or steel. The material has a relatively high compressive strength compared to its tensile strength. Furthermore, the dimensions of the arch ribs have no correlation to the heaviness of stone construction. The slenderness of the ribs demonstrates that Abraham Darby, Jr., the iron founder who built the bridge, understood the nature of the material he was working with even though he did express knowledge of the fact that the semi-circle is not the most efficient form of an arch. Unlike stone construction, the ribs are cast in complete half segments, not small voussoir blocks. The slenderness of the ribs is allowable because, unlike a stone arch, the cast iron can resist a certain magnitude of tensile stress materially and structurally because the iron arch segments are mechanically connected. When analyzing Ironbridge, the System Form, apparently characteristic of stone construction, needs to be balanced by the Component Form. When analyzed at this level, Ironbridge is both materially appropriate and adapted.

Later cast-iron bridges are similarly criticized as being substitutions for stone because they are built of actual voussoirs.[59] Again, the arch form itself is an adapted System Form to cast iron. Like stone, cast iron has relatively small span limits when used as a beam and is susceptible to brittle failure under dynamic load. The Southwark Bridge in London typifies the voussoir type cast-iron arch. (**Fig. 5.13**) A cursory glance reveals that the voussoirs do appear stone-like, however their component form is different. The voussoirs of the Southwark Bridge are made of vertical plates enclosed on all four sides by plates oriented perpendicular to the orientation of the vertical plate. This form is more materially efficient than stone and reflects the nature of the material. Other cast-iron arch bridges used voussoirs that are cast in shapes far more complex with the intention of minimizing the material used. (**Fig. 5.14**)

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[58] **Ref. Appendix A-01, p.A.25-A.26**.

[59] Keller.

Fig. 5.13: Southwark Bridge, London. John Rennie, 1819. (Peters)

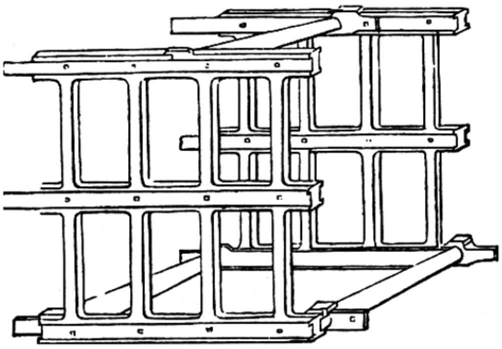

Fig. 5.14: Cast-iron voussoir segment designed by the American Thomas Paine. Englishmen R. Burdon and Th. Wilson used such segments to build the Sunderland Bridge across the River Wear in England in 1796. (Peters)

These examples show that so-called substituted forms are not necessarily incorrect or bad uses of material. On the contrary, the new materials were better suited to the application than the original materials in the above examples.

5.6.4 Some Conclusions on Material Substitution

The question posed in the Introduction, "*How do materials transcend the substitution phase to the status of being material-adapted?*" is not accurate. The use of stone by the Greeks to make beams was a choice made by the fact that stone was the superior material available for the application. This perhaps poses a dilemma in how a form is qualified as material-adapted because there is an issue of what application best *uses* a material versus what material best *serves* an application. Perhaps a distinction between material-adapted and application-adapted needs to be considered in further development of the model presented in this thesis.

Materials are not used substitutionally when first discovered. This section described how reinforced concrete was first used in adapted forms that were distinctively different from the established materials before it was used in more familiar forms that are associated with other materials. However, even these applications respected the nature of the material. Plywood has always been used in adapted ways because it was designed specifically to address the deficiencies of natural wood. Its structural use was developed in a novel structure, the airship, when there was little precedence of its use in structural applications.[60] (**Appendix A-04, p.A.226, Fig. 60**) Similarly, aluminum was used structurally on a limited basis for only ten years before Zeppelin built his airships.[61] Both of these materials were developed in adapted ways and were only used substitutionally when they offered superior qualities to whatever material they were replacing for the application. This summarizes the nature of substitution. Why would one material be substituted for another if not for the fact that the new material offers superior qualities? On this basis, it can be concluded that the original material was a substitute for the new material until the new material was available to take its place. Finally, the developer of materials should not dismiss the value of substitution as a tool for learning about and gaining experience with a new material. This knowledge and experience can lead to ideas about how to use the material in more adapted ways.

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[60] **Ref. Appendix A-04, p.A.209-A.230**.
[61] **Ref. Appendix A-09, p.A.373-A.376**.

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TEST CASE: FIBER REINFORCED POLYMERS

06

6.1 Introduction

This chapter will use the development of fiber reinforced polymers (FRP) to test the applicability of this thesis to the development of new materials. FRP is a relevant test case because it is an emerging material in civil engineering applications. The historical evolution of FRP has interesting parallels with the historical evolution of aluminum, plywood, and reinforced concrete. These parallels are relevant to developers of FRP today. They can aid the developer's understanding of the progress the industry has made and what the possible future of the material is.

This chapter will briefly review the properties and historical evolution of FRP materials. It will show how the various influences described in **Chapter 04** have affected the development of FRP and examine how the evolution of FRP has parallels with the evolution of other engineering materials. This chapter will conclude with recommendations for the material's further development and predict the possible future of the material in civil infrastructure applications.

6.2 Properties of Fiber Reinforced Polymers[1]

FRPs are composed of two or more distinct constituent materials. The base components are fibers and a matrix binding material. Sandwich components can be made with various core materials faced with FRP panels. Some core materials are corrugated FRP sheet, wood or foam 'solid' core, and honeycomb that can be made of various materials. Unlike reinforced concrete, the fibers in FRP receive and transmit the principal compressive and tensile stresses. The matrix binds these fibers, maintains the overall form of the Component, helps transfer stress between discontinuous fibers, and supports the fibers from buckling when subject to compression.

FRP materials are characterized by light weight, high strength to weight ratios, and high resistance to environmental degradation. The mechanical properties of FRP are primarily determined by the mechanical compatibility of the fibers and matrix, the adhesion between the fibers and matrix, the orientation of the fibers and the direction of loading. The optimum properties of resin and reinforcement cannot be obtained unless there is an effective bond

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[1] General sources for this section are: Gordon[2], p183-201; Keller[1], p13-22; Swanson, p1-7; and Murphy, p.ix.

Table 6.1: Mechanical Properties of Glass, Carbon and Aramid Fibers

Property	**Unit**	**E-Glass Fibers**	**Carbon Fibers**	**Aramid Fibers**
Tensile Strength	MPa	3,500	2,600 to 3,600	2,800 to 3’600
Young’s E-modulus	GPa	73	200 to 400	80 to 190
Elongation at failure	%	~4.5	0.6 to 1.5	2.0 to 4.0
Density	g/cm^3	2.6	1.7 to 1.9	1.4
Thermal coefficient of expansion	10^{-6}/K	5 to 6	axial -0.1 to -1.3, radial 18	-3.5
Fiber diameter	µm	3 to 13	6 to 7	12
Fiber structure		isotropic	anisotropic	anisotropic

Source: Keller, 2001 (after Flemming)

between the fibers and matrix; this is a constant objective of FRP production, design, and processing.[2]

Matrix materials are classified as either thermoplastics or thermosetting polymers (thermosets). Thermosets cure by chemical reaction. This is an irreversible process that means that it will not melt back into liquid with the addition of heat. Thermoplastics can be plastically formed repeatedly by heating than to an elevated temperature. Thermoplastics can also be heat welded. The most common thermoplastics are nylon and polypropylene. Thermosets are the most common matrix material used in FRP structures today.[3] The most common thermosets are unsaturated polyester resins (UP resins), epoxy resins (EP resins), and vinylester resins (VE resins). All of these common matrix materials are sensitive to ultraviolet (UV) radiation. Additives, coatings and/or surface fleeces can protect them.

The three main fiber types used in infrastructure applications are glass, carbon and aramid. The United States Air Force has used boron fibers for components in jet fighters but this material is too expensive to use and a health hazard to work with. Properties of the principal fibers are given in **Table 6.1**.

Glass fibers are the most commonly used in structural applications. They are made by melting glass in an electrically heated platinum cistern and drawing fibers from small teat-like holes in the bottom of the cistern. The glass is hard and cold by the time it reaches the revolving drum beneath the furnace. A coating is sprayed on the fibers to prevent them from sticking to one another on the drum and to improve the bond with the matrix.[4] Commercial glass fibers are 3 to 13 microns[5] thick. Fiberglass is isotropic, stronger than steel by weight, but not as stiff. The low cost and high strength to weight properties are particular advantages of glass fibers.

Carbon fibers are very strong, stiff and light. The use of carbon fibers is limited by their anisotropy (reduced radial strength) and high cost of production.

Aramid is a synthetic fiber that has high tensile strength. The disadvantages of aramid fibers are their low compressive strength, reduced long-term strength (stress rupture), and their sensitivity to UV radiation.

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[2] Murphy, p ix.
[3] Keller[1], p16.
[4] Gordon[2], p183.
[5] …about a third to half a thousandth of an inch.

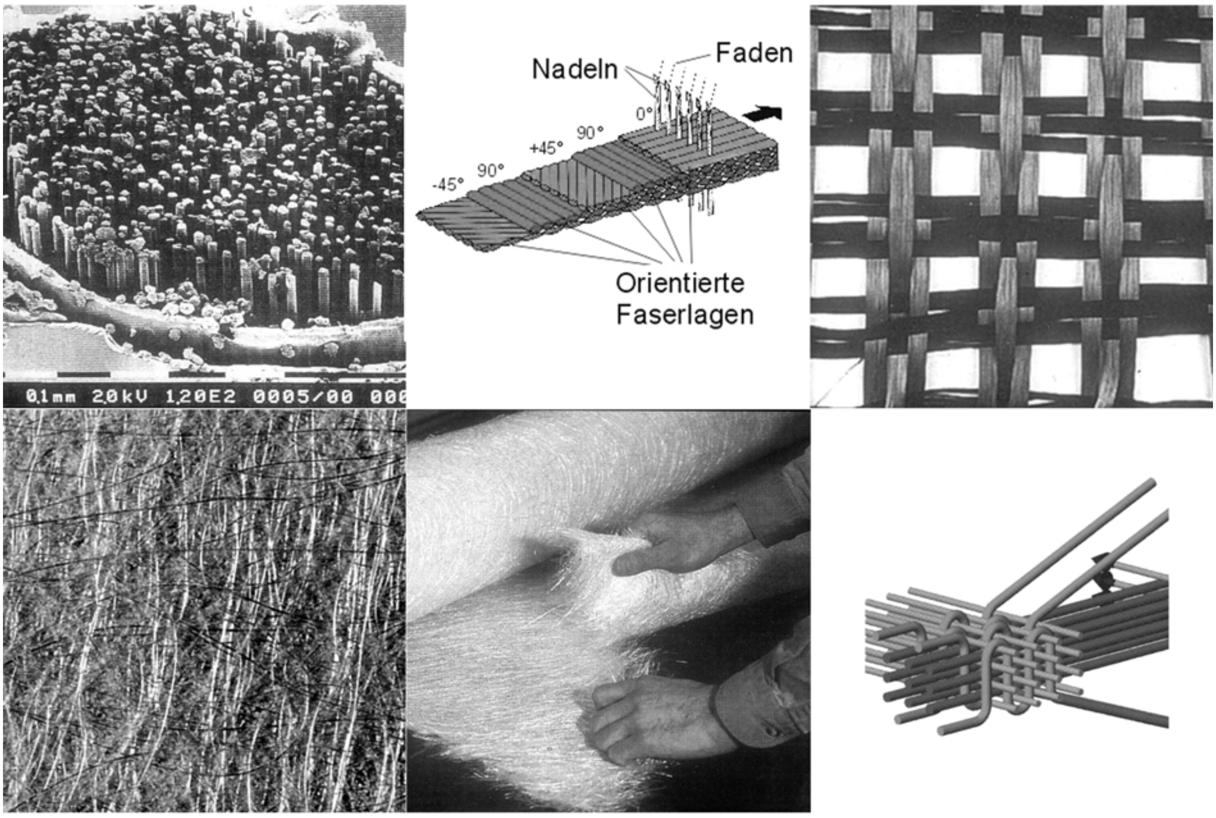

Fig. 6.1: Different fiber base architectures. (a) Parallel fiber strands (roving). (b) Multi-axial non-woven fabric. (c) Grid fabric, for grid reinforced concrete. (d) Continuous Fiber Mats. (e) Fleece (chopped glass fiber strand mat). (f) Three-dimensional woven fabrics. (CCLab, after Flemming)

Fibers can be used in a multitude of arrangements. The strongest arrangement is if the fibers are parallel. Like plywood, the strength of a FRP component will differ depending on the orientation of the fibers and quantity of fibers oriented in any one direction. Bundles of parallel strands are called roving. Different textiles can be made such as multi-axial non-woven fabric, grid fabric (e.g. for grid reinforced concrete), continuous fiber mats, fleece or chopped glass fibers, and three-dimensional woven fabrics. (**Fig. 6.1**)

It is difficult to mold complex shapes with long fibers because the fibers have a tendency to crinkle, which reduces strength. Chopped fiberglass mat is the most common arrangement because it is easy to handle and manufacture into complex shapes. It is difficult to get more than about 50% by volume of fibers into a material, especially if using weaves or mats, because the fibers do not compress well. The strength of fiberglass mat is somewhat less than a third of parallel strand. Even so, chopped strand mat will generally surpass mild steel strength for weight. It is almost impossible to get isotropic properties in practice using a fibrous material because of the difficulty in getting fibers to pack tightly and point in all directions. In any case, the theoretical strength of such a three dimensional, random arrangement of fibers would be one-sixth that of an all-parallel system, which would not be very useful.[6]

The stiffness of glass fiber composites is generally inferior to steel, and wood when gauged by stiffness to weight ratio. The weight, strength and stiffness of carbon fiber reinforced

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[6] Gordon, p188-189.

Table 6.2: Relative costs of some structural materials

Material	**$/metric ton**
CFRP (mats. 70% of cost, fabr. 30% of cost)	52,500 to 120,000
GFRP (mats. 60% of cost, fabr. 40% or cost)	1,950 to 4,500
Aluminum alloys, worked (sheet, bars)	1,800 to 1,875
Hard woods	600 to 1,500
Plywood	450 to 1,500
Mild steel, worked (angles, sheet, bars)	375 to 525
Soft woods	150 to 450
Concrete, reinforced (beams, columns, slabs)	192 to 270

Source: Ashby and Jones[1], 1996

polymers (CFRP) and glass fiber reinforced polymers (GFRP) are compared with other common engineering materials in **Table 4.2.**

The main disadvantage of FRP material against materials like wood, steel and reinforced concrete is their cost. (**Table 6.2**) Cost competitiveness depends, in part, on how important weight reduction and environmental resistance is to the overall function of a particular application. This chapter will address other ways to make economical issues more favorable to the use of FRP.

6.3 Processing Technologies[7]

There are a variety of processing technologies that can be used to make FRP components. This section reviews the most common processes.

Hand Lay-up

Hand lay-up is historically the most common method for making large FRP structures such as boat hulls, airplane parts, and most of the FRP buildings built from the 1950s to 70s. (**Fig. 4.24**) Complex shaped components can be made with good quality using the hand lay-up method. The major disadvantage of this process is that it is labor intensive. A large number of plies are needed for thicker parts because the individual plies are relatively thin (approximately 0.13 mm, or 0.005 in).

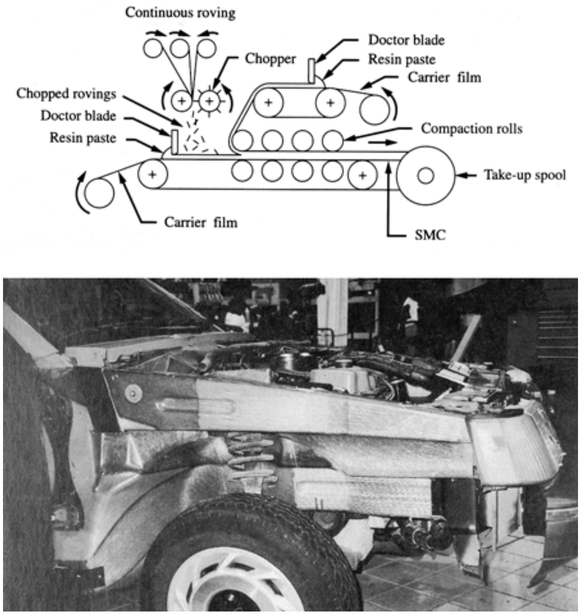

Fig. 6.2: (a) Schematic of production process using sheet molding compound (SMC). (b) Automobile part made with SMC. (Swanson)

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[7] General source for this section: Swanson, p8-17.

Sheet Molding Compound

Sheet molding compound (SMC) is made by chopping glass fiber and adding a resin mixture to create a sheet molding material that can be cut into lengths and placed into matched metal dies under heat and pressure. (**Fig. 6.2**) This process can achieve high production rates and has been used to produce automobile body panels.

Filament Winding

Filament winding consists of winding continuous-fiber tow around a mandrel to form a structure. (**Figs. 6.3**) The mandrel typically rotates while the fiber-spinning unit is synchronized to move back and forth longitudinally. Filament winding has been used to make glass-fiber pipe, rocket motor casings and sailboard masts. The advantages of filament winding are its automated process and typically low manufacturing costs. This method can be designed for high production rates. Filament winding is most readily used for making convex shapes, but there are a number of techniques under development to make more complicated shapes.

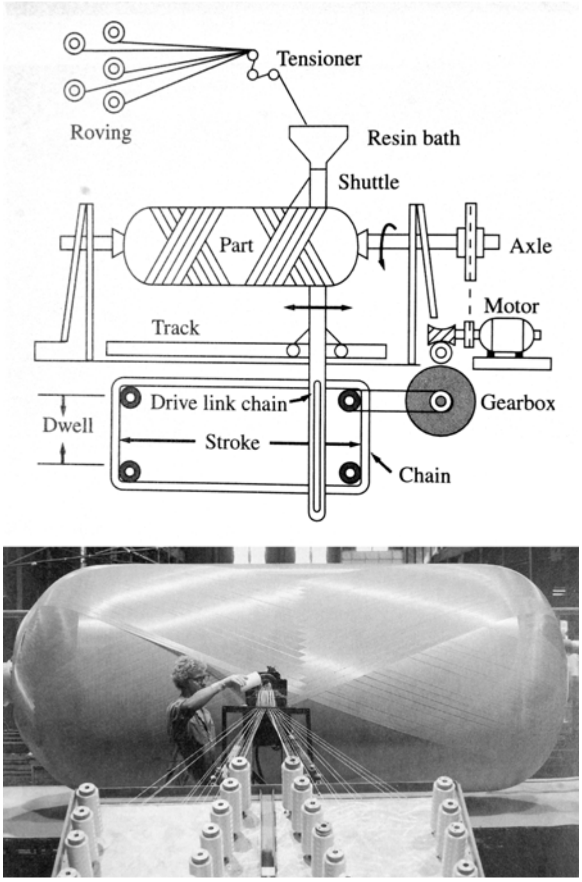

Fig. 6.3: (a) Schematic of filament winding process. (b) FRP product being processed by filament winding. (Swanson)

Compression Molding

Compression molding forms components from thermoplastic sheets by compressing the sheets in a heated match-cast metal die. (**Fig. 6.4**)

Fig. 6.4: Compression molding using thermoplastics and match cast metal dies. (Swanson)

Resin Transfer Molding

Resin transfer molding (RTM) uses a dry-fiber preform made of cloth that is placed in a mold where resin is introduced. This technique is suitable to a certain level of automation and ensures good part geometry control. RTM optimizes the proportions of fiber and resin volume, which reduces waste. RTM is now used in large molding applications such as boat hulls, which are usually constructed using the hand lay-up method until recently.[8]

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[8] Jacob[2], p36-43.

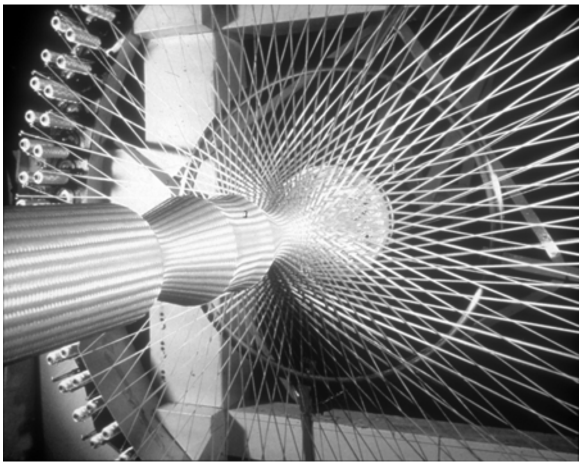
Fig. 6.5: Braiding. (Swanson)

Braiding

Braiding is a traditional textile process adapted for use with glass, aramid and carbon fibers. (**Fig. 6.5**) Tubular products can be braided on a mandrel to vary the section size of the component and then placed in a RTM mold. Braid patterns are typically two-dimensional but fibers can be oriented in the through-the-thickness direction. The braiding process is used to make tubular forms of variable dimensions.

Pultrusion

Pultrusion makes linear FRP components by pulling fibers through a resin bath and then through a heated die. (**Fig. 4.22**) The pultrusion process is similar to the extrusion process used for aluminum except the fiber is pulled rather than pushed. Pultrusion can produce cross-sections of equal complexity as those produced by extrusion. Pultruded structural components are commonly used in civil infrastructure applications today in a variety of profiles. Most profiles are similar to standard steel sections. (**Fig. 4.21**)

6.4 History of FRP Materials and Applications

6.4.1 Plastic[9]

The early development of plastic began with original research in Europe in the nineteenth century and was commercially exploited in the United States. Styrene was invented in 1831, melamine in 1834, vinyl chloride in 1835, and polyester in 1847. Alexander Parkes, a trained metal worker and manager of the casting department of a Birmingham, England foundry, started to experiment with rubber in 1846. The rubber industry was only twenty-five years old at the time. The vulcanization process was new. It was independently developed by Charles Goodyear in America and Thomas Hancock in England. Parkes altered the process for manufacturing cellulose nitrate, also known as guncotton, to make Parkesine, a material that is capable of being cast, stamped, carved and painted. When the material cures it is very hard. Parkes exhibited Parkesine at the Second Great Exhibition in London in 1862. Parkes was unsuccessful in commercializing his product.

John Wesley Hyatt, an American with no formal training in chemistry, independently invented Parkesine, which he called Celluloid. Hyatt, a printer by trade, invented Celluloid in response to a $10,000 dollar reward offered by a billiard ball manufactory to anyone who could find a substitute for ivory in making billiard balls. Ivory was in short supply at the time. Hyatt succeeded in making a Celluloid billiard ball in 1869. He introduced camphor to neutralize the instability of the cellulose nitrate.

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[9] Source for this sub-section: Quarmby, p11-17.

The commercial success of Celluloid led others to search for other new materials that could be profitable. Some plastic materials invented before 1900 are: polyvinyl chloride, patented by Baumann in 1872; polymerized methylacrylate, patented by Kohlbaum in 1880; urea formaldehyde, created but not patented by Hölzer in 1884; cellulose acetate, created by Cross and Bevan in 1894; and Polycarbonate, created by Einhorn in 1898, but was not marketed until 1959.

In 1907, Leo Baekeland, a Belgian chemist working in the United States, received a patent for phenol-formaldehyde, the material that came to be known as Bakelite. Variations of phenol-formaldehyde had been known since 1872, but Baekeland was the first to find a way of controlling the fast reaction between phenol and formaldehyde. The slowed reaction enabled the material to be molded. Bakelite was widely successful. It was used in a broad range of products from gears to gramophone records. It was particularly successful in electrical equipment such as switches and solenoids. Baekland's financial success encouraged other chemists to work further on synthetic materials, especially materials that could overcome the inadequacies of Bakelite. Bakelite had to be laminated with paper or cloth because it was brittle and could only be made in colors that ranged from brown to black.

Hans John patented ureaformaldehyde in the United States in 1918, even though it had been known since 1884. John marketed the material as an adhesive and as a material for impregnating textiles. John invented a variation of the material that was hard and transparent when cured. This led to the search for a synthetic substitute for glass. In 1929, William Chalmers, a professor at McGill University in Montreal, found that the polymers of methacrylic ethylester and methacrylic nitrite produced a hard, clear material. His discovery was marketed by companies in the United States and Britain as polymethylmethacrylate and sold for a modest cost in 1934. It was used as a synthetic glazing material for airplanes during World War II.

World War I emphasized the importance of a large-scale chemical industry, and World War II led to the industry to mature and become more organized. Up until that time, plastics chemists were still employing the 'pick and mix' method of chemistry, whereby they would just mix something together and see what happened. The basic monomers had been known for almost a century, but neither they nor the mechanism of polymerization were understood. Hermann Staudinger, a German chemist, published his theory that plastic materials were composed of giant molecular chains in 1922. This led plastics development to become more scientific and precise.

The plastics industry in Germany was spurred just prior to and during World War II because of that country's need to be independent of materials from outside Europe. Production of synthetics increased exponentially in Britain and the United States as well during the war when sources of natural rubber were cut off. In the United States, production of all synthetic rubbers in 1942 amounted to 3,600 tons. By 1945, US production of one British-developed range alone was 725,000 tons.

A fundamental shift in plastics research occurred immediately after World War II. Up until that time, a material was discovered and then the means of exploiting that material were investigated. The new direction of research focused first on identifying the properties desired of the material and then the material was developed. Bayer’s discovery of polyurethane while searching for a material comparable to nylon is a typical example of this research and development process. Since the 1950s, this tendency to produce materials tailored to a specific need has only grown.

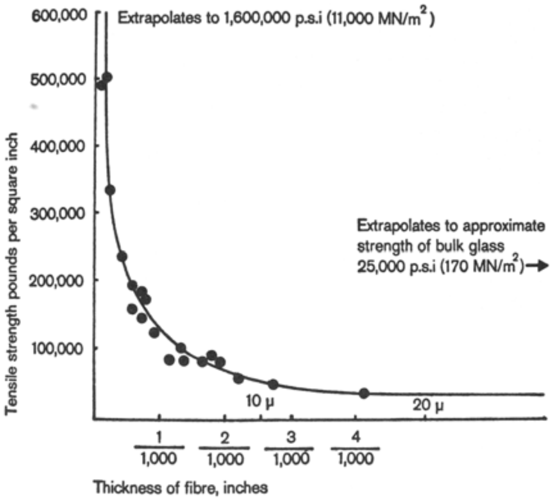

Fig. 6.6: Graph showing increase of glass fiber strength as diameter diminishes. (Gordon^2)

6.4.2 Fibers

Glass Fibers

A.A. Griffith, an English materials scientist then working at the Royal Aircraft Establishment at Farnbourough, England, made the first experiments with glass fibers in the 1920s. Griffith was seeking to determine the reason why there are large variations between the strengths of solids. Griffith used glass as a ‘model material’ to confirm his theory about the relationship between of surface energy and strength. Glass was simpler to experiment with than wood or steel. Griffith found that the strength of glass increased the thinner it was drawn. (**Fig. 6.6**) From this research fiberglass was developed, being first used to make radar-domes mounted under the Lancaster bombers of World War II to detect submarines.[10]

Carbon Fibers

The first carbon fibers can be traced to Thomas Edison, the American inventor. Edison made electric lamp filaments by heating bamboo fibers. Bill Watt, an English materials scientist, produced the first viable carbon fibers for structural purposes in 1964 at Farnborough, England. Watt was able to carburize plyacrylonitrile fibers, which are used to make the dress-fabric ‘Courtell,’ under special conditions to produce a fiber that combined a very high modulus with substantial tensile strength. The early development of carbon fibers was hampered because of their low work of fracture.[11]

Aramid Fibers

Aramid fibers were invented by Stephanie Kwolek and Herbert Blades in 1965 while working as research scientists at E.I. Du Pont de Nemours & Company. Du Pont first introduced this fiber commercially in 1972. The para-aramid type of this fiber is marketed as Kevlar. Kevlar was originally developed as a tire chord material. Today it is used in adhesives and sealants, defense equipment, belts and hoses, and composites. Twaron and Technora fibers are similar competitors to Kevlar.[12]

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[10] Gordon^2, p73-75.

[11] Gordon^2, p198 and 200.

[12] University of Missouri-Rolla, 2001. http://www.chem.uwec.edu/Chem405_S01/malenirf/project.html

6.4.3 Early Fiber Reinforced Composite Materials[13]

The strength and toughness of weak, brittle materials is improved by the addition of even small quantities of fiber. The earliest fiber reinforced composite material was probably straw reinforced, sun-baked brick in ancient Egypt and Mesopotamia. The straw limits cracking and increases the material's resistance to Poisson effects when subject to compressive load. The Inca and Maya put plant fibers in their pottery, and English builders used to add hair to household plaster.

Papier-mâché is another composite material that was known to the Egyptians. The method of building up a papier-mâché structure or object by placing pieces of paper soaked in an adhesive over a mold is similar to modern hand lay-up methods using fiberglass mat to make boat hulls, surfboards, and other artifacts. The Egyptians made elaborately shaped mummy cases from this material. J.E. Gordon, an English materials scientist of the twentieth century, claims that papier-mâché would make an excellent material for making light, strong, shell-like structures with elaborate curvature such as for coach building, boats, furniture, etc. except for the fact that its resistance to moisture and fungi are unacceptable. Only natural glues, such as hide and starch-based glues, are suitable. Synthetic glues make the material brittle because the adhesion is too good.

During World War II, English scientist Geoffrey Pyke suggested using an iceberg as an aircraft carrier from which to guard vulnerable mid-Atlantic shipping lanes. Pyke suggested that wood pulp be added to the water before freezing to overcome the brittle properties of ice. He had shown that adding 2% by volume of wood pulp sufficiently improved the brittle properties of ice. The iceberg was to be made by adding pulp to water and allowing the water to freeze naturally in a sea-loch in Newfoundland. The scheme was abandoned when aircraft with greater range began to be produced and due to the general trend of the war.

6.4.4 Early Fiber Reinforced Polymer Composite Materials[14]

The concept of reinforcing a polymeric resin dates back to Baekland's discovery that phenolic resin could be processed with fibers to give it strength and toughness. Bakelite resin is hard and brittle when set. It was first used as an ingredient in lacquers and as an insulator in the electrical industry. It later proved to be an excellent adhesive for plywood.

Bakelite was first reinforced with short cellulose fibers such as wood-flour. Most of the early applications were as a molding powder. The dry powder can be put into a heated steel mold where it softens. The resulting viscous material then flows into the interstices of the mold when subject to the pressure of a hydraulic press. It hardens irreversibly. The first commercial Bakelite molding is supposed to have been a gear-lever knob for a Rolls Royce car in 1916. The shortness of the fibers used in Bakelite molding powder was necessary to ensure that the material would flow evenly in the mold. However, the shortness of the fibers means that the material will not have high strength.

Materials of the highest strength need to be reinforced with long fibers packed closely together. The tradeoff is that long fibers are not as moldable as short fibers. Laminates were developed in the 1920s using cellulose paper or fabric impregnated with a solution of

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[13] Primary source for this sub-section: Gordon[2], p173 and 175-177.

[14] Primary sources for this sub-section: Gordon[2], p179-180; Murphy, p.ix-x.

phenolic resin, usually in alcohol, dried, and then the impregnated sheets were laid between the carefully trued, parallel, heated plattens of a hydraulic press where they were hardened under a pressure of about 15 MPa (1 ton/in^2). The water resistance of such materials is related to the pressure under which it is formed. However, this means the hydroxyls in the cellulose must be blocked, which makes the material brittle and unsuitable for mechanical applications.

Plastics reinforced with long fibers were largely developed in the aircraft industry, which needed strong, lightweight materials. During World War I, the Germans built an airplane from a paper-based phenolic material. This application was not successful because the designers reduced the water resistance too far in order to increase toughness.

Resin stiffened fabric was used in the 1920s. Micarto, one commercialized resin stiffened fabric, was used in America to make propellers from 1920. Robert Harzell, used a mixture of fabric and phenolic reinforcement, called Hartzing, for propellers made prior to the 1940s. Aero Research UK produced a composite made from flax linen with ureaformaldehyde just before World War II.

During the World War II, researchers in Britain developed cellulose-reinforced sheet as a potential substitute for aluminum sheet to cover aircraft. They were able to reduce the total moisture movement in the plane of the sheet to 0.8% while maintaining reasonable toughness. The sheet was problematic because of its tendency to shrink and swell. It was riveted onto an aluminum frame that did not shrink and swell with it. In the desert the plastic became so taut that cracks appeared along the line of rivets, and in a wet climate the sheet buckled and waved. The dimensional movement of cellulose-reinforced materials is about 1%, or about one inch in eight feet. Metal, wood and plywood are all superior to this, therefore eliminating cellulose-reinforced materials as an option for large-scale structural applications.

The plastics industry grew fast from the 1920 onward. Plastic articles were of relatively little importance in industry or for domestic products prior to 1920. In 1930, the American plastics industry produced about 17,000 metric tons (37,500,000 pounds) valued at about $75,000,000, or $2 a pound. By 1940, the production volume grew by a factor of eight to 136,000 metric tons (300,000,000 pounds), the cost still averaging around $2 per pound. By 1944, production more than doubled with an output of approximately 317,500 metric tons (700,000,000 pounds) valued at $1,800,000,000, or about $2.50 a pound. The potential for the growth of lightweight, strong materials was recognized and it was predicted that the plastics industry was just beginning.[15]

6.4.5 The Emergence of Modern Fiber Reinforced Polymer Composite Materials

Modern reinforced plastics date from the introduction of inorganic fibers towards the end of the World War II. GFRP was used first used to make radomes. Radomes must be made from electrically non-conducting materials to be transparent to radar. GFRP satisfies this requirement while providing the strength to support the structure.[16]

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[15] Allen[1], p472.

[16] Gordon[2], p183.

The first use of a composite as a primary component of an airframe was probably in the fuselage of the English Spitfire fighter aircraft produced by Gordon Aerolite. The composite was used because of a threatened aluminum shortage. SAMPE (the Society for the Advancement of Material and Process Engineering), states that the first official application of GFRP to an airframe was as a sandwich panel used in the aft fuselage skin of the American Vultee B-15 trainer in 1945.[17] There was some initial resistance to use glass fiber as reinforcement because it was unproved. These doubts were resolved when 3M introduced glass fiber reinforced tapes in the 1940s.[18]

The aircraft industry continued to develop these materials after World War II. GFRP sheets were used as interior panels to protect the fuselage of planes used by Pennsylvania Central Airlines. The lining protected the metal fuselage skin from contact by heavy cargo during loading and unloading. The Plastics Division of the Continental Can Company manufactured the finished panels using Fiberglas, manufactured by the Owens-Corning Fiberglas Corporation.[19]

A wide range of applications for GFRP emerged in the 1940s. Ray Greene probably built the first GFRP boat in 1942, using a new toughened resin from American Cyanamid. However, the GFRP boat industry did not grow greatly until chopped fiberglass mat became available in the 1950s. The Darrin and Stout Scarab car bodies were built using GFRP cloth seven years before the Corvette. Six flying cars that actually flew were built using GFRP in 1946. The development of a compression molded GFRP tub for the Kirby Apex washing machine was a particularly significant development because it moved FRP materials into the mass-production sector. The higher temperatures and pressures required by mass-production became the driving forces behind the future development of resins, reinforcements, and additives.[20]

FRP use expanded greatly in industrial applications such as chemical tanks, pipes, and ductwork during the 1950s. Growing consumer affluence in the post-war period created FRP markets for leisure boats, sports car bodies and sporting equipment. Two major polyester resin developments occurred in the 1950s. The Atlas Powder Company, an American chemical company, created Atlac, a bisphenol-A furmarate polyester that was purchased in powder form and made up with styrene by the users. The Durez Division of the Hooker Chemical Company, also an American chemical company, created Hetron, a chlorendic polyester based on HET-acid reacted by glycols. Hetron is highly resistant to strong acids and oxidizing acids.[21]

Chopped strand glass mat became available between 1952-1955. Within a few years of the introduction of polyester resins, they were being used with glass reinforcement to construct boat hulls and car body moldings. Sixty percent of small boats were built using this material within five to six years after GFRP was first used on a commercial scale. This use spread so rapidly because the material offered clear cost and constructabilty advantages over wood or metal. This is an example of the fact that mechanical and physical properties are not the

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[17] Murphy, p.x.
[18] Murphy, p.x.
[19] Allen^2, p73.
[20] Murphy, p.x.
[21] Murphy, p.x-xi.

only factors that control the use of materials. In this case, constructive attributes were more important.[22]

As FRP materials usage increased, the limitations of the materials and molding technology became increasingly apparent. The focus of development shifted to solving these disadvantages, as they came to be recognized, particularly with respect to automating processing technologies and improving product consistency.[23]

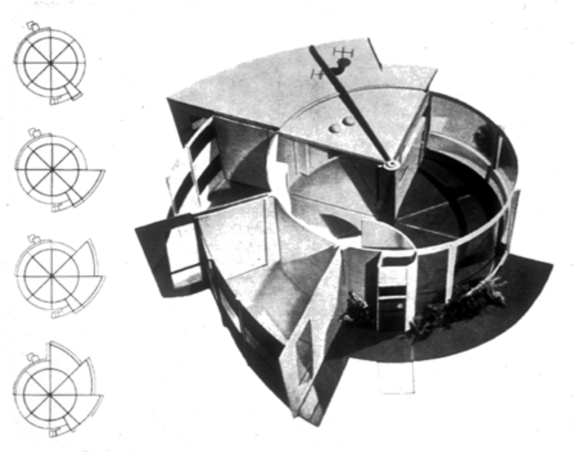

Fig. 6.7: First all-FRP house exhibited at Paris Exhibtion of 1856. Ionel Schein, Yves Magnant, and R.A. Coulon. (Quarmby)

High performance aerospace and defense applications have provided another driving force in the development of reinforced plastics. The British Royal Aircraft Establishment led the development of CFRP in the late 1950s, but it took some years before they reached production components because the early fibers were too brittle. The Wright Patterson Air Force Base Materials Laboratory, in the United States, introduced carbon fiber composites in the fins of F-14, F-15 and F-16 fighters in 1974 and, two years later, boron fiber-reinforced epoxy was also used for similar components.[24]

6.4.6 Application of FRP to Building Construction, 1950s-1970s

The limited range of plastics materials available before the 1950s hampered early applications of FRP to building construction. Plastics were used to make cladding panels, building blocks, window frames, light structural members and complete staircases. Arthur Quarmby, author of *The Plastics Architect*, observes that this is a case of substitution.[25] However, as per the analysis provided in **Chapter 05**, these applications should be seen as efforts to improve upon the performance of established materials. The complete staircase is a clear example of part-count reduction and indicates that the early pioneers of FRP understood this potential. Furthermore, as Quarmby points out, the materials available were limited. He should add that knowledge of the long-term behavior of the material was limited as well as the number of processing technologies to make larger, more structural forms. The cladding panels and window frames were probably made either by injection molding using some type of molding powder like Bakelite, or by pressure molding. Both processes can make components of limited size and relatively short fibers have to be used, thereby reducing their potential strength.

Considerable research and development was conducted to create structural applications in buildings in Europe and the United States from the late 1930s onward. Quarmby states that this was especially true for Britain because it experienced great material shortages during the war. In response, a number of organizations were formed to investigate possible solutions to

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[22] Potter, p.xiv; Murphy, p.xi.
[23] Murphy, p.xi.
[24] Murphy, p.xi-xii.
[25] Quarmby, p45.

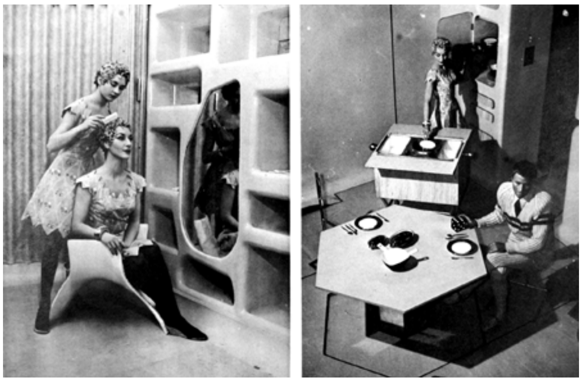

Fig. 6.8: FRP interior exhibited at Ideal Home Exhibition in London of 1956. Alison and Peter Smithson. (Quarmby)

the problem. As early as 1941, Sam Bunton and T. Warnett Kennedy, Scottish architects who worked for the Building Plastics Research Corporation of Glasgow, drew up plans for rapidly erected, flexible housing types based on a standard GRFP building panel. Their design included precise jointing techniques, and permanent internal and external finishes. Their proposal was not realized because of the socio-political instability of the post-war period. Quarmby states that there was a societal desire to rebuild familiar building types of the pre-war years, even though there was a shortage of traditional building materials.[26] This is not a problem of form-finding; it is a case of market demand. Lack of market demand continues to slow the integration of FRP materials into building structures today. Quarmby appears to confuse demand with what he perceives as need.

French architects Ionel Schein, Yves Magnant and R.A. Coulon exhibited the first all-FRP building at the Paris Exhibition of 1956. (**Fig. 6.7**) It was designed and constructed in 1955. This building was made of structural GFRP building panels and included a single-unit molded bathroom module that integrated the toilet, sink and bathtub. Other equipment, such as the kitchen, was molded into the building. The building explored modular building systems and plastics connection types. One innovation was clip-on heating modules. The finished shells, fabricated using the hand lay-up method, were of low quality and required a lot of hand-finishing and final trimming. The building was dismantled and reassembled at Douai, France, on the grounds of Charbonnages de France, the company that sponsored the building's development.[27] The difficulties Schein et al. had in manufacturing the house is indicative of the lack of high quality processing technologies and tools.

Schein, Magant and Coulon continued to design a wide range of buildings and building components after 1955. However, they did not receive the support and funding to commercialize their ideas. Quarmby blames the plastics companies for lack of vision in not supporting the activities of Schein et al.[28] However, this is another case where demand did not exist and the plastics companies were perhaps wise in directing their research efforts elsewhere.

In 1956, the English architects Alison and Peter Smithson exhibited integrally molded furnishings and some of the first GFRP shell chairs at the Ideal Home Exhibition in London. (**Fig. 6.8**) These were 'ideas' models meant to examine the way in which people might live, rather than be production prototypes of commercial products.[29]

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[26] Quarmby, p45.
[27] Quarmby, p45-46.
[28] Quarmby, p47-48.
[29] Quarmby, p49.

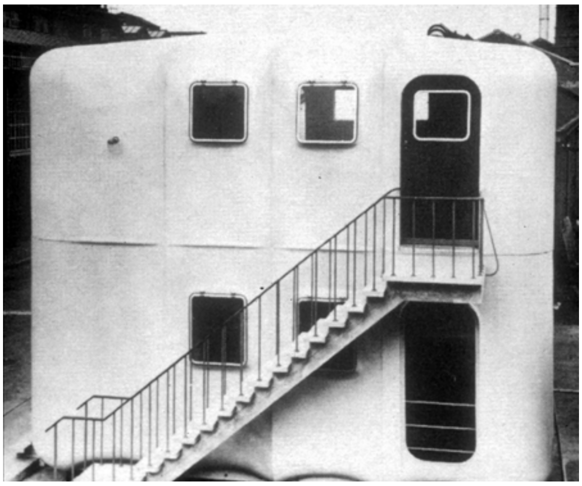

Fig. 6.9: British Railways modular FRP building system for switching stations, 1959. (Audouin)

Fig. 6.10: Folded plate FRP vault structure for a sulfer factory in Rome. Renzo Piano, 1965. (Quarmby)

The Monsanto House of the Future, designed by architects R. Hamilton and M. Goody and engineer Albert Dietz, was constructed in 1957 at Disneyland in California. (Fig. 4.9) The Monsanto Chemical Company sponsored the project. This demonstration home's chief contribution to the development of FRP materials in building construction was to demonstrate the structural potential of FRP materials. The core of the building is made with normal reinforced concrete and contains the kitchen and bathroom service areas. A glue-laminated ring beam is used as an anchor point to which the GFRP structure is mounted. The GFRP structure of the living area is comprised of L-shaped units bonded together with epoxy resin to form an integral C-shaped cantilevered thin-shell structure. Two C-shaped units are placed side-by-side to form a living unit. The thin shell is made of woven fiberglass mat and a polyester resin matrix. The half-shells were formed in concave modes using the hand lay-up method. The total thickness of a shell is 7.6 mm (3/10 in). The shell is stiffened by its double-curvature geometry and by high-density polyurethane foam sprayed on to thickness of 89 mm (3.5 in). The foam is also the insulation for the building. The floors and ceilings are made from fiberglass surface layers and honeycomb kraft paper core impregnated with phenolic resin. It was originally planned to leave the original finish but construction damage required a coat of paint to be applied. Twenty million people visited the Monsanto House over ten years at Disneyland. During that time it suffered no damage from earthquakes and 145 km/h (90 mph) winds. It was demolished in 1967. The demolition contractor planned to raze the building in one day using a 1,360 kg (3,000 lb) wrecking ball, but the ball only bounced off the GFRP shell. The shell reportedly broke chain saw blades and a demolition crane only succeeded in loosing itself from its mountings. The house was finally destroyed after two weeks by using choker cables. This experience provides a model example of the potential strength of this material and is perhaps more useful as an example of the qualities of the material than the architectural form of the house itself. As Quarmby notes, this experience demonstrates the need to consider post-design life issues such as how a structure will ultimately be destroyed.[30]

The development of GFRP buildings continued throughout the 1950s and 1960s in Italy, Germany, Britain, and the United States. These buildings were mainly concept models of what FRP buildings could look like. They exploited the formability of GFRP and almost all

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[30] Quarmby, p50 and 52; Bélec, p34-35.

employed doubly curved structural panels that also served as the environmental envelope of the building. However, there are few examples of these buildings being mass-produced as their designers hoped.

A modular GFRP building system designed in 1959 by the in-house architect's research and development section of British Railways was one successfully mass-produced GFRP building system. (**Fig. 6.9**) The system was designed as modular building units that could be combined in any number of configurations to tailor the size of the building to different sized relay stations. Variations of this system were used for telephone exchanges and for a biological research laboratory used for the British Antarctic Survey. The research laboratory was designed and built by Mickleover of London Ltd. in 1963.[31]

In 1965, Italian architect Renzo Piano designed a folded-plate barrel vault structure for a sulfur factory in Rome. (**Fig. 6.10**) The fiber density and surface fleece material of the GFRP panels was varied to allow daylight to filter into the building in a controlled manner.[32] This structure exhibited an alternative structural form adaptable to GFRP materials other than the doubly curved panel system.

Fig. 6.11: Filament wound, FRP low-cost housing unit, USA. TRW Systems, 1968-1973. (CCLab)

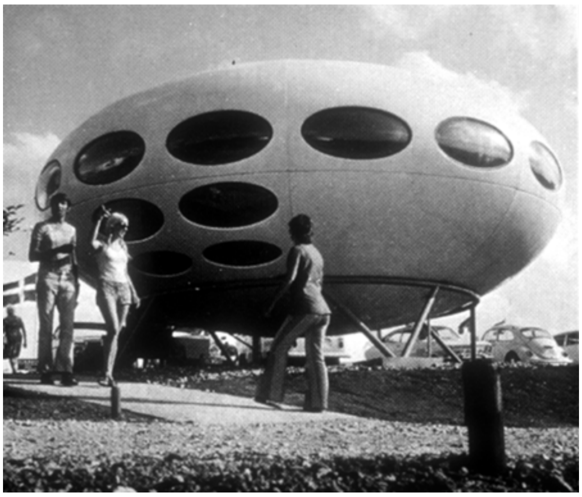

Fig. 6.12: Futuro home, Finland. Matti Suuronen, J. Ronka, and Oy Plykem, 1968. (Quarmby)

By the end of the 1960s, the designers of GFRP buildings began to address the inefficiencies of hand lay-up processing and the complexity of joining modular panels together without requiring significant finish work. Filament winding techniques, perfected in the aerospace industry, were seen as a solution to improving construction quality and production volume, and reducing costs.

From 1968, TRW Systems Corporation, USA, produced modular buildings designed by Ezra Ehrenkrantz for a low-cost housing program sponsored by the United States Government. The system consisted of prefabricated buildings units that could be made in variable geometries using the filament winding production process. The most typical geometry was rectangular. (**Fig. 6.11**) These buildings clearly reflect a more conservative design ideology than reflected in most of the experimental GFRP buildings built to that date. This surely reflects the fact that the consumers in the housing market did not want such futuristic building forms represented by the space saucer-shaped Futuro home, also built in 1968. Matti

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[31] Quarmby, p52-59.
[32] Quarmby, p69-65.

Suuronen, J. Ronka, and Oy Plykem, of Finland, designed the Futuro house. (**Fig. 6.12**) Over 1,800 fiber shell homes were built throughout the United States by 1973, in contrast to the production of about thirty Futuro homes.

Wolfgang Feierbach, a German architect, tried to strike a balance between cultural expectations of housing forms and the particular processing and constructive attributes of GFRP materials. Feierbach's Kunstoffhaus, built in 1968, was made of a simple, modular panel system that fit together to make a rectangular frame structure. (**Fig. 6.13**) The overall rectangular form was a more conservative approach to GFRP housing design but he still expressed the nature of the material in the concave surfaces of the sidewall panels. The form of these panels express the static function of the moment resisting corner connections and the processing attribute that the panels were made in forms.

Development of GFRP buildings continued into the 1970s before the continued market resistance to expressed GFRP buildings and the world oil crisis brought the GFRP building experiment to a stop. A couple of notable GFRP buildings built in the 1970s are the filament wound BASF Tube House, designed by Franz U. Dutler of Germany in 1970, and the large thin-shell canopies designed by Pae & Broughton to cover the terminal building of the Dubai Airport in the United Arab Emirates in 1972. (**Figs. 6.14 and 6.15**)

6.4.7 Hiatus and New Start of Development, 1970s-1990s

From the mid-1970s to the early 1990s there is a dearth of real development of FRP civil infrastructure applications. Most development of FRP materials was limited to aerospace and defense applications. Throughout the 1980s, FRP continued to be used to a limited extent in

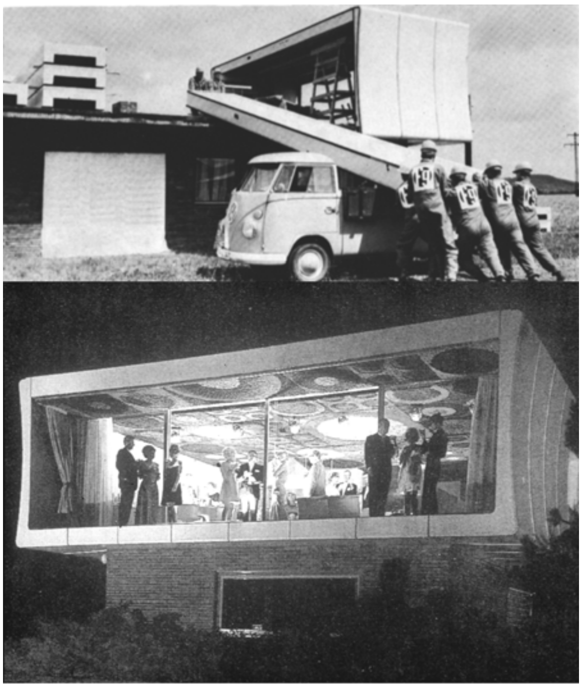

Fig. 6.13: Kustoffhaus, Germany. Wolfgang Feirerbach, 1968. (CCLab)

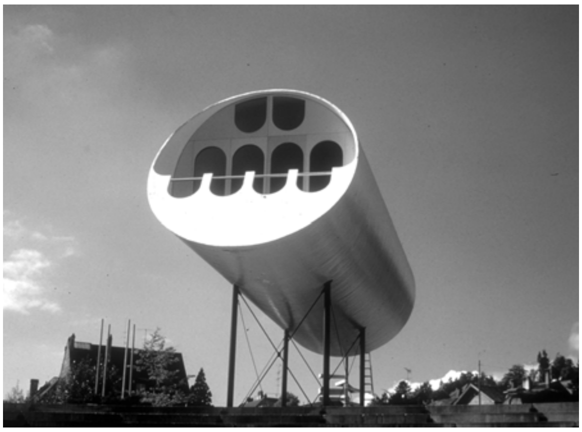

Fig. 6.14: BASF Tube House prototype, Germany. Franz U. Dutler, 1970. (CClab)

Fig. 6.15: FRP roof of Dubai Airport, United Arab Emirates. Pae & Broughton, 1972. (CCLab)

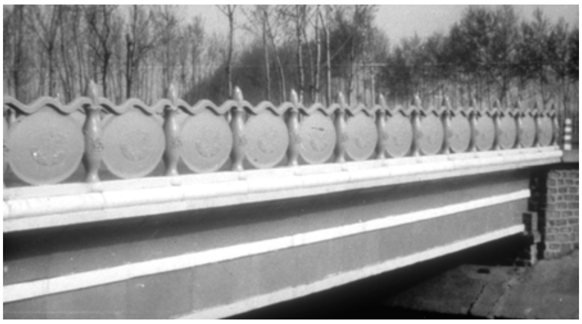

Fig. 6.16: Miyun Bridge, first all-FRP bridge in the world, China, 1982. (CCLab, after Meier)

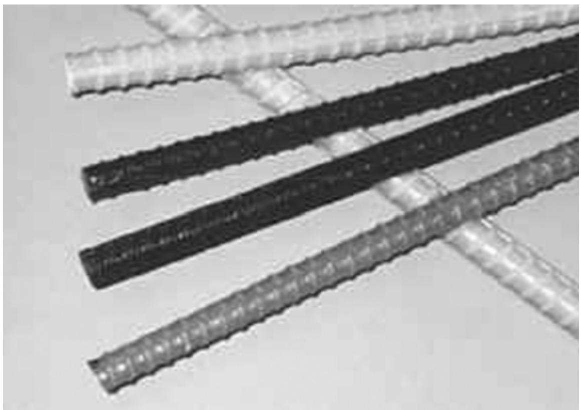

Fig. 6.17: GFRP concrete reinforceing bars. (CCLab, after Documentation C-Bar)

Fig. 6.18: Example of FRP sheet reinforcement of existing reinforced concrete bridge pier. (CCLab, after Sika)

the automobile industry, primarily for high performance racing and sports cars. Towards the latter half of the 1980s, FRP began to be increasingly used for sporting goods such as fishing poles, tennis rackets, golf clubs, and bicycle frames. Civil infrastructure use was very limited. The Chinese developed FRP for bridge applications from the 1970s. The Miyun Bridge, a single span, two lane bridge with 20.7 m span, was the first all FRP highway bridge in the world when it was built in 1982.[33] (**Fig. 6.16**) However, little further development of consequence occurred for FRP bridge structures until the late 1980s.

FRP use in bridge applications increased in the early 1990s because of the age of post-World War II infrastructure, which were affected by steel corrosion, and two major earthquakes in California and Japan in the early 1990s.

GFRP reinforcing bars began to be used in concrete to avoid the problems of corrosion that plague steel reinforcement. (**Fig. 6.17**) GFRP is somewhat problematic to use because it is buoyant in the concrete, which requires special measures to hold the bars in their proper position. GFRP is also susceptible to degradation because of the alkalinity of the concrete. Epoxy-coated steel bars seem to be preferable.

By 1984, FRP sheet products became available for strengthening and repair applications. The use of FRP sheet and strip products for strengthening purposes increased greatly in the United States after the Northridge earthquake of 1994, and also in Japan after the Kobe earthquake of 1995. (**Fig. 6.18**) The Japanese orientated the fibers of the sheets vertically to increase bending resistance, and the fibers were orientated horizontally in the USA to increase the deformation capacity. **Figure 6.19** shows the

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[33] Keller[1], p74-75.

annual consumption of carbon and aramid fiber sheets for strengthening in Japan between 1993 and 1997. These graphs are representative of the general trend of increased FRP use during the 1990s.[34]

In 1994, Lockheed Martin, an American aerospace company, constructed an all-FRP box-girder bridge using aircraft technology. The box-girder was a hand-laminated, U-shaped girder connected to a pultruded FRP bridge deck. Martin Marietta Materials, a spin-off company of Lockheed Martin, developed this system further when it fabricated a similar bridge with an integrated deck and superstructure for the Smith Road Bridge in 1997.[35] (**Fig. 6.20**)

In 1999, Thomas Keller, director of the CCLab at the EPF-Lausanne, used CFRP cables to strengthen the Verdasio Bridge in Ticino, Switzerland. (**Fig. 6.21**) This is the first instance in which that CFRP cables have been deviated. Before construction, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) investigated the allowable radius of deviation of carbon fiber cables, which are sensitive to lateral pressure.[36]

From 1997, there has been a steady increase in the number of FRP bridge decks. Several all-FRP bridges have been built, mostly pedestrian bridges such as the trussed Pontresina Bridge in Graübunden, Switzerland, or the cable-stayed Fiberline Footbridge in Kolding, Denmark; both built in 1997. (**Figs. 6.22 and 6.23**) Both of these bridges are built with pultruded FRP Components and their System and Component Forms are similar to steel.

Few buildings were built from the mid-1970s through the 1990s. In 1993, Ayman S. Mosallam, a professor in the Composite

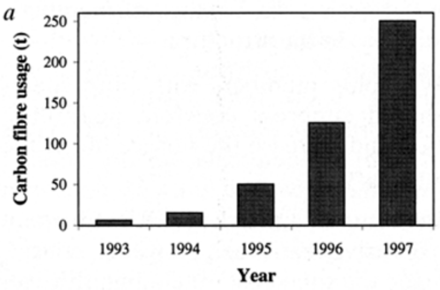

Fig. 6.19: Consumption of carbon fiber in Japan between 1993 and 1997. (CCLab, after SEI 4/99)

Fig. 6.20: All-FRP Smith Road Bridge, USA. Martin Marietta Materials, 1997. (CClab, after Martin Marietta)

Fig. 6.21: CFRP cable strengthening of Verdasio Bridge, Switzerland. CCLab, 1999. (CCLab)

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[34] Keller^1, p61-65.
[35] Keller^1, p75.
[36] Keller^1, 65.

Fig. 6.22: All-FRP Pontresina Footbridge, Switzerland. CCLab, 1997. (CCLab)

Fig. 6.23: Cable-stayed Fiberline Footbridge, Kolding, Denmark. Fiberline, 1997. (CCLab, after Fiberline)

Structures Group at the George Washington University in Washington, DC, could only cite a handful of examples of the use of pultruded FRP structures in the ten previous years.[37] The most significant structure is the turret of the Sun Bank Building in Orlando, Florida. The base dimension of the turret is 10.67 m x 10.67 m (35 ft x 35 ft) and its height is 6.10 m (20 ft). (**Fig. 6.24**) Other examples included platform structures used in industrial areas where corrosive products are present, and frame structures used in electrical installations where the material's low electrical-conductivity is beneficial. Single-story frame structures have been built in the USA and the UK. The Strongwell Company in Virginia, USA, has constructed several pultruded FRP portal framed buildings and a five-story stair tower frame.[38] (**Fig. 6.25**)

6.5 State of the Art

6.5.1 General

FRP use is generally increasing today in a wide range of domains. The aerospace, defense and boat industries continued to lead the development of FRP design, but the automotive industry is driving the development of processing technologies for mass production components that must meet strict quality, weight, and cost parameters. The FRP market for special civil infrastructure applications such as power line transmission poles and wind turbines has been steadily increasing the past five years. The use of carbon and aramid FRP strips and sheets for strengthening and repair continues to increase, particularly in seismic areas such as California, Southern Italy, and Japan. Pultruded FRP Components currently dominate the FRP market in construction.

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[37] Chambers, p33.
[38] Cosenza et al., p265.

6.5.2 Bridges

Two principal types of bridge deck structures emerged in the 1990s. Both types are sandwich structures. One system uses FRP laminate face sheets with either a solid foam core, such as that produced by Hardcore Composites (Delaware USA), or with a honeycomb core, such as that by Kansas Structural Composites (Kansas USA). (**Figs. 6.26 and 6.27**) The second type of deck to emerge is the pultruded sandwich section with hollow cores. Such decks are made by a variety of manufacturers and each has a patented cross-sectional geometry. The most successful decks used today are the Duraspan Deck developed by Martin Marietta Composites (North Carolina USA), and the Advanced Composite Construction System (ACCS) developed by Maunsell Structural Plastics (Beckenham UK). (**Figs. 6.28 and 6.29**) It is not clear why the pultruded systems are emerging as the superior deck types. The Kansas Deck had problems with crushing from wheel load, causing the face panel to separate from the honeycomb core. Hardcore lost a contract to build 100 decks in Ohio because it was unable to move its production facility to that state by a contract determined date. The contract for the second phase of Ohio's "100 deck" program was granted to Martin Marietta. Therefore, it is not clear if the pultruded systems are succeeding because they are necessarily better or if better-run companies are marketing them.[39]

Any all-FRP bridges being built today, mostly footbridges are made from pultruded FRP Components in typical steel configurations. (**Fig. 6.22**) Various pultruded FRP girders are being tested. They usually have both glass and carbon fibers. (**Fig. 6.30**) There is little or no development of more complex geometries as used for the Smith Road Bridge. (**Fig. 6.20**)

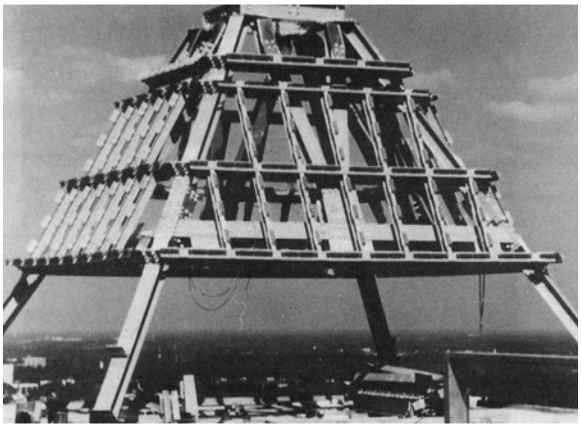

Fig. 6.24: Pultruded FRP structure of the Sun Bank turret, Orlando Florida, c.1990. (Chambers)

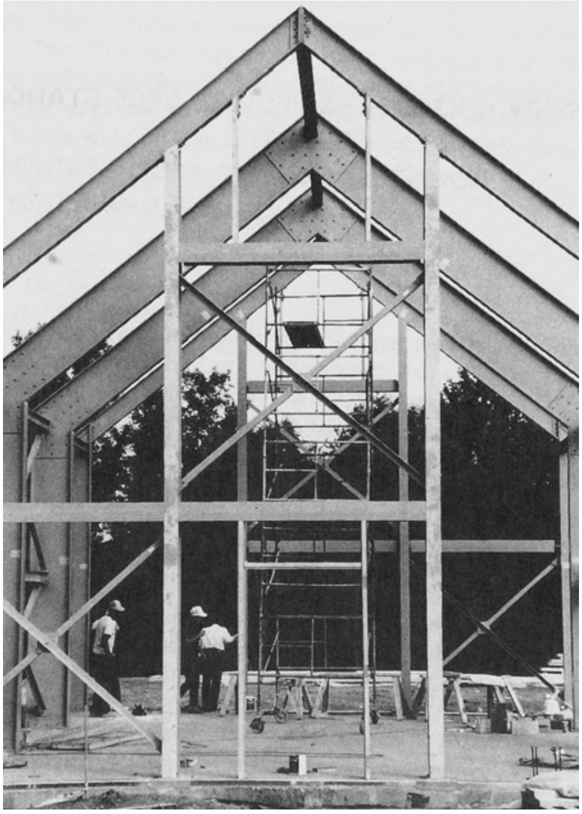

Fig. 6.25: Pultruded FRP portal frame, USA. Strongwell. (Cosenza et al.)

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[39] When I contacted Kansas Structural Composites for a state of the art report written by Thomas Keller in 2001 (Keller[2]), the company did not appear to be well organized.

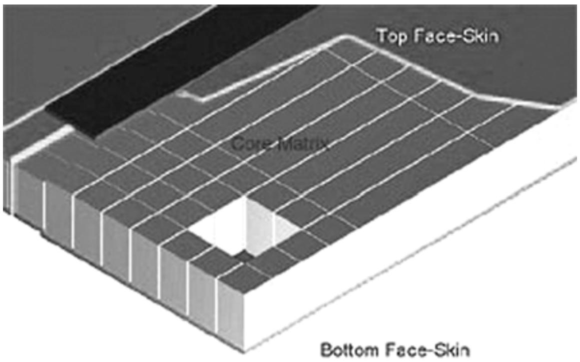

Fig. 6.26: Hardcore bridge deck system. Foam core sandwich. (CCLab, after Hardcore)

Fig. 6.27: Kansas bridge deck system. Honeycomb sandwich. (CCLab, after Kansas)

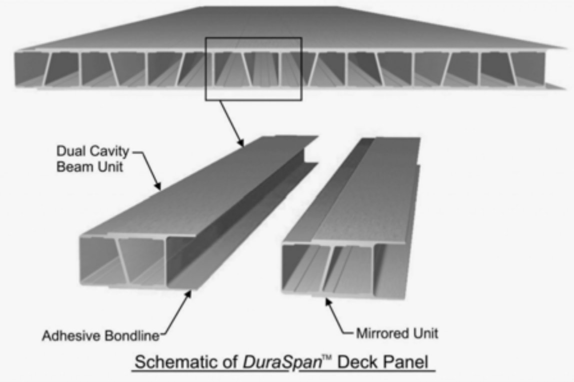

Fig. 6.28: Martin Marietta Composites Duraspan bridge deck system. Pultruded, hollow core sandwich. (CCLab, after Martin Marietta Composites)

6.5.3 Buildings

The largest FRP building built in recent years is the Eyecatcher Building in Basel, Switzerland. (**Fig. 6.31**) Artevetro Architects of Basel and the CCLab designed this building in collaboration with Fiberline Composites A/S of Kolding, Denmark. The Eyecatcher was built for a building exposition held in 1999. It is five-stories tall, making it the tallest all-FRP building structure yet constructed. Its pultruded GFRP frame is made of built-up Components. During design of the building it became apparent that the translucent GFRP sandwich panels used to let light into the sides of the building could be used structurally, though this idea could not be incorporated into the building at the time. (**Fig. 3.2**) It was also determined that such sandwich panels could be filled with an insulation material like aerogels to comprise a single-layer, integrated building system.

More recently, a single-component staircase with handrail was designed and built by the architect Toshiko Mori and boat builder Eric Goetz. Goetz has expertise in the design and construction of complex FRP structural forms.[40] (**Fig. 6.32**) Similarly, the winning design proposal for a new Australian Antarctic research center was won by a design team composed of the Australian architects Allen Jack + Cottier, engineer Hyder Consulting and boat builder Jutson Yacht Design.[41] (**Fig. 4.6**) The use of boat builders highlights the fact that engineers and architects using FRP in civil infrastructure have not learned to design FRP from the Element level. Instead, they use off-the-shelf products such as sheets, strips and pultruded FRP Components that come with pre-determined structural characteristics to which the application must be adapted. It is preferable to tailor the material to the application. The future of FRP structures clearly lies in this direction since it does not

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[40] Ivy, p200.
[41] Powell, p24-27.

appear FRP will be able to compete head-to-head against steel or reinforced concrete on a cost basis when used in identical System and Component forms.

6.6 The Influences and FRP Development

6.6.1 *Introduction*

The developer of FRP materials can benefit from an analysis of the influences described in Chapter 04 on FRP. Such an analysis allows the developer to understand where that development has been, what has been achieved, and what failed. Perhaps the developer can better see what the future development of the material may produce with this knowledge.

6.6.2 *Function*

The first all-FRP house was exhibited in 1956, over a decade after the post-war rebuilding effort was under way. This house demonstrated the constructive possibilities of FRP but also promoted a radical departure from the way people were used to live. The experimental houses that followed, such as the Monsanto Home of the Future, the Furturo House and the BASF Tube House all promoted radically new housing forms for which there was no apparent market. Immediately after World War II the aluminum industry made similar attempts to redefine the housing form by applying aerospace construction technology to domestic dwellings. Buildings of larger scale were built too, such as airplane hangers and large meeting halls.[42] This development abruptly stopped at the end of the 1950s, coincidently with the emergence of the FRP experimental building development. Why the FRP industry thought it would succeed where the aluminum industry failed

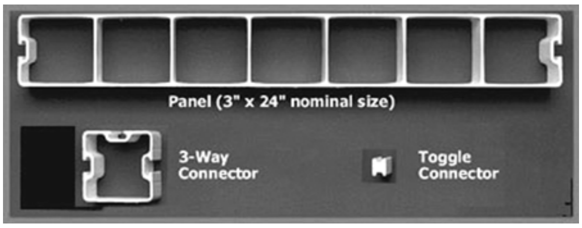

Fig. 6.29: Maunsell Advanced Composite Construction System. Pultruded, hollow core sandwich. (CCLab, after Maunsell)

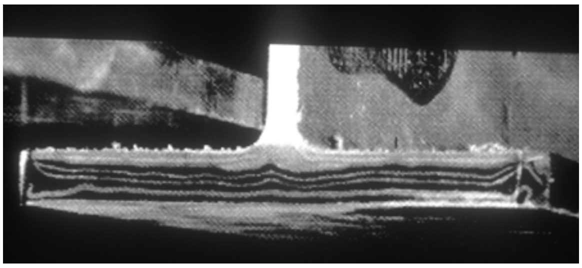

Fig. 6.30: GFRP **I**-section with carbon fiber reinforced flanges. (CCLab)

Fig. 6.31: Eyecatcher, Basel. Tallest all-FRP building at 5 stories. Artevetro Architects and CCLab, 1999.

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[42] Ref. Appendix A-09, p.A.377.

should be further researched. Nonetheless, the FRP industry sponsored housing prototypes that did not meet the expectations of the market. The effort to make FRP into a standard building material failed. That is, they promoted products for which there was little or no demand.

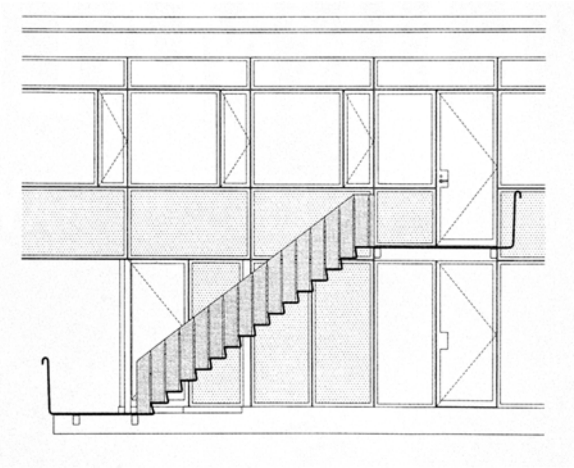

Fig. 6.32: All-FRP, integral, mono-unit staircase design. Toshiko Mori, archtiect; Eric Goetz, boat builder, 2003. (Ivy)

The most successful FRP building programs were sponsored by government agencies. These programs were the British Railways switching stations and the modular, filament-wound, low-cost housing units produced for a United States government-housing program by TRW Systems. FRP building development stopped in the mid-70s, probably a combination of little success and the global oil crisis. The pioneers of FRP development were clearly more interested in exploring the potential forms of FRP materials and promoting a different lifestyle than trying to first establish the material as a viable competitor to conventional materials like wood in the United States and reinforced concrete in Europe. In other words, their Function Pattern, though arguably appropriate for the material, was not correct for the market.

There was no real development of FRP in bridge structures until carbon and aramid fiber strips and sheets began to be used for strengthening and repair in the 1980s. The need for such products increased exponentially after the North Ridge and Kobe earthquakes in 1994 and 1995 respectively. The potential market for FRP materials in bridge structures increased when the corrosion-related deficiencies of conventional steel or reinforced concrete bridge structures could no longer be ignored at the end of the 1980s and early 1990s. Departments of transportation (DOTs) in the United States and Europe became increasingly aware that many bridges built in the post-war period were deficient because of corrosion problems. The state of bridges in the United States, where approximately 200,000 bridges are considered to be structurally deficient, best illustrates the magnitude of this problem. This situation has led to a clear market opportunity for FRP materials to be considered more seriously, particularly since DOTs are more aware of life-cycle costs related to operations and maintenance costs than they were in the past. Unfortunately, no corresponding need has been identified to justify adapting FRP materials to building construction.

6.6.3 Material Properties

One of FRPs most favorable characteristics is its high strength to weight ratio. While this characteristic may be useful in bridge structures, it is not generally a critical factor in buildings. The beneficial strength to weight ratio of glass or aramid fiber composites is offset by their relatively low stiffness to weight properties. Therefore, FRP materials need to be developed to take advantage of other properties that make it economically competitive to conventional materials.

The lack of stiffness of GFRP materials can be overcome by form. Stressed-skin, doubly curved structural forms effectively augment the material stiffness. This is apparent in the monocoque shell of the Monsanto House. However, these forms were not amenable to the function pattern of housing in the past and arguably still not today. Such forms do not satisfy the cultural and aesthetic expectations of what a house should look like or compliment contemporary living styles.

Another problem with FRP materials is that there are still several critical issues of material behavior and properties that need to be better understood. Creep and fire behavior are two examples. Also the high thermal coefficient of expansion of plastic materials causes great difficulties in the design of connections for plastics structures. This in one of the reasons why the design of joints in prefabricated plastics structures requires more attention than is usual in more orthodox structures.[43]

FRP's resistance to corrosion and environmental degradation is a significant advantage in buildings and bridges. This property is the single most desirable for bridge applications because it ameliorates the high maintenance and repair costs of corroded steel and reinforced concrete structures. The impermeability, low thermal conductivity and resistance to degradation are amenable to the material's use in single-layer building systems whereby FRP panels are used as environmental barriers. FRP has been variously used in such applications, but without full integration of these properties with its structural potential. The experimental buildings from the 1950s to 1970s took advantage of all these properties and their System and Component Forms should be studied in more detail to see how they can be adapted to be less radical aesthetically and spatially.

Though FRPs lightness is of limited importance in buildings and bridges when they are finished, this property can be useful to reduce transportation and construction costs because lighter structural Components do not require the same heavy equipment as steel.

Finally, the designer's ability to tailor material composition and architecture of Element Form is a great advantage to optimizing the use of the materials. For instance, the GFRP Components can be reinforced in critical areas with carbon fibers, thus benefiting from the excellent strength and stiffness properties of carbon fiber without the cost associated with an all-carbon fiber structure. (**Fig. 6.30**)

6.6.4 Processing Technologies

The ability to form FRP materials into forms with compound curves or with complex cross sections is a great advantage of FRP materials. The thickness of the material can be easily varied to provide zones of greater stiffness or strength. Early FRP building components were mostly fabricated by hand lay-up methods. Little development work was done to industrialize the processing of FRP components except for buildings like the BASF Tube House and the TRW Systems low-cost housing modules that were made using filament winding technology. Though pultrusion and filament winding were both developed in the 1950s[44], it is not clear why the former was not used at all or why filament winding was only first used at the end of the 1960s.

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[43] Davies, p53 and 54.

[44] Murphy, p.x.

Hand lay-up can be used to make very complex forms, but it also requires intensive labor and time to do. Hand lay-up is uneconomical for mass production but will remain useful for one-off, specialized products because the tooling costs of alternative processes cannot be justified unless there is a minimum production volume. These production limits need to be specifically studied for building and bridge structures.

Compression molding is useful for mass production, but is limited to thermoplastics, which are presently not used extensively for infrastructure applications. Though this process requires expensive match cast dies, the cost is offset by the production volume and rate that can be achieved. It needs to be determined what the market could be for structural Components produced in high volumes. Quarmby notes that there were experiments made in the 1960s to develop mass-production methods for single-unit modular panels used to make geodesic domes and vaults, however there was no attempt to develop methods for variable geometry applications.

Filament winding is a restrictive processing system, though its potential can be greatly expanded if the technology to make convex as well as concave forms can be perfected. Filament winding might be useful for producing short-span bridges, and the service cores or stair towers of buildings. It is doubtful that people will want to move into BASF type tubes in the near future, however, TRW System's more conventional forms may be adapted to more refined systems of construction that are better detailed so they do not look like stacked cargo containers.

Pultruded profiles are currently used in bridge construction and to a lesser extent in building construction. Pultrusion is a mass-production, processing technology capable of fabricating linear Components with complex cross sections. Pultruded bridge deck systems seem to be outperforming other FRP systems such as foam core or honeycomb core sandwich systems, however the maximum size Components that can be made using pultrusion is limited, so long span bridges will have to be built up in some manner. Maunsell designed its ACCS system to be put together like Legos. It is hard to imagine that pultruded sections with steel shapes can be competitive in the future except in steel-type structures that either need to be lighter or have a high resistance to corrosion.

Vacuum-assisted, resin transfer molding seems to be the best processing system in the near future to make sandwich and doubly curved shells because of advances in technology that make it possible to fabricated large single unit components. This technology is being advanced within the leisure boat industry. RTM is efficient and produces little waste. The problem with any of the processing technologies used to make complex forms is the cost of the molds. Research has been going on in this area since the production of the compression molded GFRP tub for the Kirby Apex washing machine in the late 1940s. Production molds are not especially expensive but master molds are. Molds made by spraying on a material to a substrate has been under development since the early 1970s when John Zerning sprayed PVC over a reticulated network for the production of highly-warped paraboidal forms. The PVC shrinks when it cures and forms a leather-like minimum surface from which a female production mold can be produced.[45] More recently, Novarc, a company supported by Oxford University, Ford Motor Company, and Beeson Gregory, developed a new spray forming

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[45] Quarmby, p65.

process for rapid tooling. The technology involves robotically spraying molten steel onto a ceramic cast, which is developed directly from the computer model of the tool surface. Once cooled, the shell is removed from the cast, applied to a backup structure and is ready for use. David Field, managing director of Novarc, says the new method can cut vehicle development time by as much as five months and save significant tooling costs.[46] CAD / CAM is an important technology for improving master mold production because complex forms can be made from digital, 3-D models using automated machining tools.

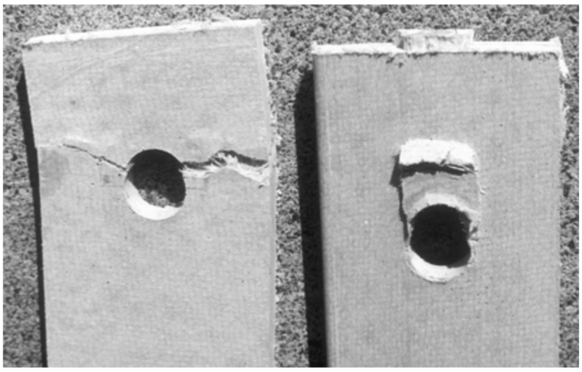
Fig. 6.33: Failure of pultruded GFRP test speciment with bolted connection. (CCLab)

The low weight of FRP makes it possible to make large, prefabricated components, which reduces the number of joints and improves the general performance of the structure.[47] The challenge today is to develop economical processing methods for producing large components that can incorporate function integrated features. As stated in **Chapter 06**, an objective of good structure is part-count reduction. FRP processing methods can produce integrated components, but more has to be done to reduce overall processing costs.

6.6.5 Connections

Adhesively bonded connections are preferable to mechanical connections in FRP structures. Developments around 1990 used FRP bolts[48], but steel works too. In either case, the designer needs to consider stress concentrations and local fiber reinforcement needs. Such special material architecture details add cost and complexity to processing. (**Fig. 6.33**)

Glued joints are preferable because they distribute the stress over a larger area of the structural Component. However, glued joints are susceptible to peeling failures. Current research in the Composite Construction Laboratory at the Swiss Federal Institute of Technology Lausanne is examining the behavior of adhesively bonded connections.[49] Further research is necessary to make design parameters more precise. Another problem with adhesively bonded joints is the variable application and curing procedures for the wide range of adhesives available. Design specifications will have to include not only the structural characteristics of the cured adhesive, but also the conditions and procedures necessary for its application. Quality control is a significant reason to prefabricate as much of the FRP structure with adhesive connections in the controlled environment of a production plant. Reliable, non-destructive methods to control the quality of bonded joints will have to be developed to avoid building regulations requiring redundant systems such as the addition of mechanical connections.

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[46] Hazen, p11.
[47] Davies, p53.
[48] Chambers, p46.
[49] Vallee.

An alternative to adhesively bonded connections can be heat welding. However, heat welding is only possible with thermoplastics and the dominant matrix materials are thermosets. Thermoplastics have the additional benefit of being easily recycled.

The aesthetic qualities of joints have to be considered carefully if the FRP Components are going to be left exposed.

6.6.6 Construction Process

The processing technologies of FRP materials are amenable to the creation of forms more complex than reinforced concrete. Unlike reinforced concrete, FRP is difficult to work with *in situ*. Quality standards, such as controlling humidity while FRP Components are being made, makes it preferable to manufacture modular building Components at a central facility. The weight of FRP generally means that the size of such Components will be limited only by their maximum transportable size.

On site construction is facilitated by the weight of FRP because it requires less heavy equipment and labor to maneuver it. Function integrated components may result in increased processing complexity, but should simplify construction and reduce construction time significantly.

Construction damage like that done to the Monsanto House will have to be avoided procedurally and with close on-site supervision to take advantage of the integrated finish qualities of FRP materials. Using some type of protective material that can be removed after construction is complete can further protect FRP components. It is senseless to justify the increased material cost of FRP because it can eliminate the need for secondary cladding materials if it has to be painted and refinished. Perhaps adhesive joints can be designed to have adhesive strips that only require a piece of non-stick paper be removed to join two components like when using double-sided tape.

Pultruded FRP Components can be constructed using steel construction methods. However, more complex structures require specialized knowledge that seems to only reside in the aerospace and boat building fields. The construction industry will have to train laborers to work with these materials as they now do for carpenters, steel erectors, and rebar layers. This cannot occur without a critical market size. Therefore, it will be necessary that specialized construction teams be formed that will probably be linked to particular products.

It will be important for designers to consider the economic aspects of FRP construction. Every possible advantage should be exploited from FRP materials that will help speed construction, reduce constructive complexity, and minimize labor and heavy equipment needs. In this way, increased design and processing costs can be offset.

6.6.7 Economics

Material-wise, FRP is unlikely to become cheaper than steel or reinforced concrete. (**Table 6.2**) It is therefore necessary to seek economic advantages elsewhere. This requires life-cycle costing analysis. However, clients will have to be educated to consider the benefits of such costing methods because they are used to focusing on initial costs.[50] Life-cycle costs

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[50] Information from conversation with Grant Godwin, Vice President and General Manager of Martin Marietta Composites, 2000.

have been a mantra of the FRP industry since at least the early 1990s[51], but the industry has clearly not succeeded in selling this economic model except to a certain extent in the transportation sector.

In bridges, the cost of FRP components is justified by decreased life-cycle costs with respect to future operations and maintenance costs. Departments of Transportation have become acutely aware of these costs and are now considering them to various degrees in their cost analysis. This is not easy when government procurement procedures have traditionally valued low-cost bidding. It is therefore necessary to get governments to adopt best-value, life-cycle cost analysis procurement and contracting standards.

The economics of building structures is more complicated. Fire and building codes must be addressed at local and higher government levels. The FRP industry will have to battle the labor gap between it and established materials, as well as the construction industry's comfort and investment in working with such materials. Perhaps the FRP industry can focus on developing construction systems that take advantage of current construction practice and technology from a particular domain of construction such as steel construction. Weight is of even less importance in buildings than bridge structures, therefore value needs to be added through function integration and reduced cost of construction and maintenance. Green building provisions can be exploited by adopting fully recyclable thermoplastics.

The early FRP housing experiments explored function integration. These designs should be studied in more detail for the potential economies that can be gained through such efforts. Function integration will clearly require more design time and may require increased processing costs. These costs can be offset by reduced construction, maintenance and operations costs. FRP buildings can be designed to be very energy efficient because the material is not thermally conductive and seamless joints can be made to limit uncontrolled air filtration through the building envelope that either draws warm air in during the summer or hot air out in the winter.

6.6.8 Socio-Political

The early FRP development was driven in part by government and industry sponsored development. The historical record indicates that the designers actually developing these materials were as interested in developing new life styles as they were in developing the futuristic forms possible with FRP when it is used most efficiently. Government sponsored research was sporadic, as government is apt to be. The FRP industry failed to collectively develop the material for civil infrastructure applications and individual companies did not maintain sustained research and development programs. It is not clear why different companies later in that first development period continued to support non-marketable building types from the 1960s to the end of this first period of development in the mid-70s.

The current period of development can be traced to the early 1990s. A joint market development group called the Market Development Alliance (MDA) was organized in America in 1993, after Owens Corning Fiberglass, an industry leader, curtailed much of their research and development of GFRP materials at the end of the 1980s because of new management. The MDA's twenty-three founding members applied to the United States Army

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[51] Chambers, p10-11.

Corps of Engineers and received three Contract Product Advancement Research contracts to design, produce and install new, improved beams, decking and pilings and to work on concrete repair methods for marine piers. This led to further projects in the United States, including the twenty-five FRP bridge decks installed through 2002.[52]

The bridge market is clearly open for FRP applications. The biggest market is currently for FRP sheet and strip products used for strengthening and repair. The second largest market is for bridge decks. This development will continue to be driven by government agencies responsible for transportation infrastructure. The National Composite Center (NCC) in Dayton, Ohio USA, runs one of the largest programs. NCC is managing a pilot project to replace one hundred conventional bridge decks with FRP decks.[53] The market for all-FRP bridges has yet to really make great inroads except for a number of pilot road bridge projects. Safety is probably a large factor in the current state of progress. Most new all-FRP bridges are being built for pedestrian use, which at least allows some knowledge to be gained about the long-term behavior of such bridges to be assessed.

The development of FRP buildings is less advanced. The problem today is the same as forty years ago. There is no overwhelming demand to change current practices for this new material. Viollet-le-Duc illustrates three important aspects of the introduction of materials to the building market – cultural, knowledge and experience.[54] The second and third aspects will be addressed in the next sub-section.

New materials culturally challenge established aesthetic precepts. Time has to be given to allow the design profession to assimilate a new material, or rather the market has to adapt to the material. Any new developments need to respect current market expectations of form and functionality. Formal and aesthetic changes can be phased in as they were with reinforced concrete. This will require some inventiveness on the parts of the designers and manufacturers to produce forms that both exploit and make efficient use of FRP – a necessity for economic reasons, while respecting current aesthetic design norms.

6.6.9 Knowledge and Technological Thought

There are a lot of unknowns about FRP materials and their long-term behavior. Aspects such as fatigue life and compressive response need to be predicted more accurately.[55] More information on FRPs performance when subject to fire, the behavior of adhesively bonded connections, and the development of ductile failing mechanisms needs to be established. With this knowledge, design allowables can be decreased to minimize the conservativeness of current design practice that decreases the material's economic competitiveness. Nonetheless, knowledge about FRP materials keeps increasing. The most significant problem is the dissemination of that knowledge.

It is imperative that the industry gets design professionals, engineers and builders into workshops to learn about the potential of these materials. The material has to be introduced to architectural and engineering students now because there is a certain factor of novelty involved with FRP materials at present that makes it seem that the material is too

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[52] Sweet, p7.
[53] Hazen^1, p9.
[54] Viollet-le-Duc, p66-67.
[55] Jacob^1, p34-38.

unconventional or advanced. This maybe intimidates designers. Corresponding to this effort should be the development of clear design principles and methods for learning how to design from the Element Form level of FRP. A major disadvantage of pultruded products is that they do not educate designers about how they are made. Instead they are marketed as finished products with Component level properties that can be used for analysis.

It should be recognized that patented proprietary knowledge limits growth of the industry by limiting the dissemination of knowledge. Such protection is useful in an initial period of development to reward those who take the larger risk of establishing a material than those who work with a material that is already established. Nevertheless, more knowledge transfer, particularly across interdisciplinary lines, should be a goal of the industry. The major composites journals[56] do a fairly good job at looking at the industry as a whole, though infrastructure issues do not receive great attention. Does this have something to do with the market potential of this industry or is it just that so little is actually happening in this sector right now?

Within the industry itself, architects are going to boat builders for expertise. This has to do with the fact that the boat builders know both design and construction, giving them an advantage of knowing the limits of what these materials can do. Engineers in civil engineering are using pre-designed Components, which does not help them understand the nature of the material well enough. It is imperative that designers of FRP structures understand and know how to apply knowledge of the processing and constructive attributes of the material. This is one aspect that designers of the early FRP housing prototypes deserve credit for. They were intimately involved in both design and production and this sensitivity should not be underestimated.

6.7 Comparing the Evolution of FRP to other Materials

6.7.1 Introduction

The focus of this thesis is the development of form. Closely linked to that development is the broader subject of material evolutionary characteristics. From the research made for this project, I have found that can be classified in one of four evolutionary groups. Those groups are: *Found Materials; Ferric Metals; Non-Synthetic Composite Materials;* and *Materials of Science*. Each group has particular characteristics that might be useful in examining the history of a material being developed today. **Appendix A-09** includes several chronologies of material evolution. Characteristics of these chronologies, in combination with data from the case studies, are chronicled in **Appendix A-10**. The materials examined are categorized by evolutionary group. Though this study was outside the immediate scope of the project, it is relevant to this chapter because the knowledge learned from this study is useful when examining the past development of FRP and making sense of current trends. This section will compare the evolution of FRP with several engineering materials and be used as a basis for predicting its future development.

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[56] *Reinforced Plastics*; *Composites Technology*.

6.7.2 Aluminum

Aluminum and FRP are both materials of science that cost more by weight than conventional materials. Both materials were first exploited in aeronautic and small boat applications. The aluminum industry was far advanced and organized in comparison with FRP during World War II. After the war, the aluminum industry was better prepared to redirect their production efforts to peacetime products. During the late 1940s and 1950s, the American engineer R. Buckminster Fuller and others used aluminum to develop advanced building systems. These systems were mainly based on either stressed skin structures using aircraft construction technology or geodesic and spatial truss systems. (**Figs. 4.26, 4.38, and Appendix A-09: p.A.379, Fig. 33; p.A.381, Figs. 38 and 37; pA.382, Fig. 39**) These developments were primarily supported by the aluminum industry, as chemical companies similarly supported the early development of FRP building types.

This phase of aluminum building system development abruptly ended towards the end of the 1950s. I have not found the reason why. Two possible factors stand out. Aluminum was seen in the 1950s as a high tech material. The aluminum can was introduced in 1956. Could the mendacity of this application have eroded people's perception that aluminum was a novel, futuristic material? Also, the first FRP house was exhibited in 1956. Another coincidence? Possibly, the decade-long experiment of aluminum structures was enough to prove that aluminum could not economically compete against steel or reinforced concrete in primary structural applications. The FRP experiment lasted almost twenty years, though this can be partially explained by the fact that processing technologies were being developed at the same time. Each successive generation of technology may have been enough to make someone think, "Surely this new technology can make FRP buildings affordable."

The development of aluminum was heavily subsidized by government in its earliest years by the French Government and again in during World War I by the American government. Likewise, government research laboratories in Britain and America developed FRP for defense applications. There was little government-funded research for the application of these materials to building structures except during the World War II. The FRP British Railways switching buildings and TRW Systems' low-income housing in America are exceptional examples of government support.

Aluminum has had limited application in bridge construction because of its cost. Most examples of its use in bridges date to the 1950s. The Arvida Bridge, an arched highway bridge in Quebec, Canada, is the most exceptional example of an all-aluminum bridge to be constructed. (**Appendix A-9, p.A.381, Fig. 36**) It has a span of 91.5 m. Aluminum offers similar weight and maintenance advantages as FRP, however recent bridge developments do not include aluminum as they do FRP.

Aluminum has become a niche product in building structures where its weight is of minimal importance to material selection criteria. Aluminum is primarily used in secondary structural applications such as window frames and façade systems. The extrusion process makes it possible to produce linear aluminum Components with highly complex, optimized sections. This is particularly useful in window frames and curtain-wall systems to account for the complex construction details of windows and the fact that a gasket has to be inserted to break the thermal bridge of the aluminum while maintaining the structural integrity of the Component. Aluminum's lightness and strength in curtain wall construction is useful for transferring wind load to the main structure and minimizing gravity load. Aluminum's corrosion resistance is a major reason why it is used for façade systems because it minimizes expensive maintenance associated with steel or wood products. These qualities are not necessarily critical parameters of the main structure and the higher cost of aluminum cannot be justified.

An advantage of FRP is that it has a low thermal conductivity and can be used to make single-layer building envelopes. The history of aluminum in building construction should be researched in detail to determine the reasons for its lack of success in primary structural applications. This is relevant to FRP because FRP will continue to be more expensive than conventional materials, weight for weight, into the future. The example of aluminum should be considered a warning to the FRP industry that FRP could be relegated to being a niche product if strong measures are not taken to bring the economic costs in line with conventional building materials. It is not likely that FRP can be successful in buildings in pultruded, steel-like forms because this results in the current multi-layer building systems typical of steel and concrete frame structures today. Clearly, function-integrated forms such as those used in the early days of FRP experimentation must be adapted to current architectural norms. These forms minimize the need for secondary materials for insulation, the environmental envelope, interior finishing, etc.

6.7.3 Plywood

Plywood was developed specifically to overcome the deficiencies of wood. FRP is partially the result of developments made to make synthetic adhesives for plywood. FRP became a possible replacement for both plywood and aluminum in airplane construction.

The early development of structural plywood dates only to the first decade of the twentieth century when it was employed in airship and airplane construction. The plywood was molded into complex forms for this purpose. Indeed, the first monocoque airplane fuselages were made of plywood. (**Appendix A-09, p.A.219, Fig. 52**) During both World Wars, plywood continued to be used in complex forms for airplane and boat construction.

After World War II, the plywood industry stopped research and development for advanced applications in the aeronautic and small boat construction industry. The industry abandoned these markets to exploit the huge housing market after the war. They marketed a flat panel form of plywood used for sheathing and flooring in lightwood framing systems. On walls, the plywood acts structurally as a shear wall for lateral stability and as a surface to mount a protective siding material. However, the sheet form of the plywood does not take advantage of the potential form complexity that can be achieved using that material. There were some experiments using sheet ply to make folded plate structures and small stressed skin roofing structures, but these are exceptional examples and have not been widely used.

It is not realistic to assume the aerospace industry will abandon FRP materials since so much research and development has occurred within the industry. Plywood's performance during the two World Wars left the impression the material was inferior because of cases where it was damaged by water. Without the plywood industries' commitment to overcome the perceived deficiencies of plywood, the aeronautic industry stopped using the material. In any case, aluminum satisfies most of the current needs of the industry. FRP is simply considered an alternative, not a wonder material. The Boeing aerospace company recently decided to limit FRP use in their proposed 7E7 jet liner and aluminum was used to construct the main truss of the International Space Station.

Since the 1970s, FRP has been used most extensively in building construction as an exterior cladding material, but its potential strength and suitability for structural purposes has not been exploited. The FRP industry should be cognizant of the history of plywood to avoid industry ambivalence about its role in developing advanced applications of its material. The precedent of combining the non-structural aerodynamic envelope with the skeletal structure of the airplane fuselage to create the monocoque structural type should be seen as an inspiration of how similar integration of function can be achieved using FRP to create single-layer, function-integrated building systems.

6.7.4 Reinforced Concrete

FRP, as a material, is most like plywood because it is a fibrous composite in which the fibers must resist both compression and tension. It is also like aluminum because it is a product of science, is relatively expensive compared to more conventional materials, and can be molded or pultruded into complex three-dimensional surface-active forms and linear Components with complex cross sections. The goal of the FRP industry is not, however, to be a niche product in the construction industry like aluminum and plywood. Rather, the FRP industry wants its material to directly compete as a primary structural material against steel, wood, and reinforced concrete. Reinforced concrete, another type of composite material, offers the best example of material evolution to model the development of FRP.

Reinforced concrete was, like FRP, introduced into a building market that was not particularly looking for a new material. That market in the late-nineteenth century was already having enough trouble trying to assimilate itself to the nature of iron and steel construction. Entrepreneurs of reinforced concrete exploited resistance of the public and the architectural profession to adapting to iron and steel. They offered an economically competitive alternative to stone construction that could be made into the familiar forms of that material. The reinforced concrete pioneers exploited this market niche admirably without fundamentally changing the aesthetic and functional expectations of the market. The success of reinforced concrete has to be partially attributed to this fact, and the fact that these forms could be made by respecting and exploiting the material’s processing and construction attributes.

In contrast, the pioneers of FRP construction tried to not only introduce a new material, but a new way of living. This was counter to the prevailing cultural mood, the space age not withstanding. Modern modes of living were being instituted. Plastic indeed became a prominent fixture in the home in the form of appliances and durable goods. It was too much to expect people to accept space age, curvilinear forms that completely broke with architectural convention. This was their biggest mistake.

Reinforced concrete is notable for its low cost of entry for entrepreneurs. The cement industry was already established for foundations and mortar. Reinforced concrete’s other constituent parts – sand, aggregate, water and rebar, are relatively cheap. The first pioneers were also contractors. They could rely on the ready labor force of carpenters to make forms.

Therefore, the situation was more favorable to concrete's success then the current situation with FRP. Though chopped fiberglass mat is relatively inexpensive, hand lay-up is a time and labor-intensive process requiring skills not typical of the building trades. Using any of the more mechanized forming technologies requires a large investment. Unfortunately, the material- and process-adapted forms created by hand lay-up were not acceptable to the building market.

Finally, there are interesting parallels between the proprietary systems of reinforced concrete prior to 1900 and today's proprietary FRP bridge deck systems. This stage in a material's evolution has to be view as necessary to reward those who are taking the risks to make the material be accepted and used on a wider basis. The success of these systems will engender wider interest from more risk averse persons in the industry and then, as with reinforced concrete, there will be a push to make design and production less restricted by the limits of the proprietary system. The state of FRP development can be interpreted to be in a period similar to that for reinforced concrete prior to 1900. The future success of the material will depend on the success of today's proprietary systems. Perhaps within ten or fifteen years, the material will have been established and accepted as a viable alternative to steel and reinforced concrete. During this period the material can be expected to be marginally economical against other materials, but that is all right as long as it leads to increased application. Once this stage is over, FRP will enter into a period of transition after a class of students has learned about the material in university, as students such as Eugène Freyssinet learned about reinforced concrete from his professor Charles Rabut. If reinforced concrete is successful at marketing itself as a primary structural material, then more adapted forms can expect to emerge once the design market opens and more minds are applied to the problem.

6.8 The Future of FRP Materials

There is nothing fundamental to change about the actions that need to be taken to expand the use of FRP materials. The same criteria have been written and re-written over the past thirty years.[57] The main actions are[58]:

- *Develop design protocols for specialized applications*. Though the use of pultruded FRP Components is a useful means of getting a wider range of architects and engineers to use FRP materials, it does not further the end objective of getting designers to design FRP structures from the Element Form level. Pultruded FRP components give a kit of parts that have pre-determined properties that are selected from standard product catalogs like steel sections. There will remain a market for such products but these products do not realize the full potential of FRP because the designer does not adequately consider the processing and constructive attributes of the material during the form-finding process.
- *Establish and promote new triad/quadratic engineering/design team comprising composite materials specialists, designers, civil engineers, and contractors*.

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[57] Davies (1964); Chambers (1993); Cosenza et al. (2001).

[58] Parameters in *italics* defined by Douglas S. Barno, in Chambers, p14.

- *Modular construction (most common elements, "Lego-type products", etc)*. Modular construction has to intrinsically allow for diversity and flexibility of how components can be derived. Building and bridge systems need to be adaptable to a wide range of Function Patterns. Designers have to learn what the minimum production volume limits for the various processing technologies are vis-à-vis economics to better tailor their design methodology to small volume, single unit construction, or high volume production. Building systems have to be integrated into the design process such that the conceptual phase of such integrated components and production tooling is not prohibitively expensive even for small volume or single-unit products. This is where the development of CAD/CAM and cheaper mold production systems will be important. Perhaps the size of building components can be tailored to the scale of the building, using smaller elements in smaller buildings to achieve the same minimum part production volume to justify tooling costs. Part-count reduction is the ultimate objective. Economic studies need to better clarify how the increased costs of Component design and processing are offset by decreased construction costs due to reduced constructive complexity, and other life-cycle costs. Life-cycle costs are the mantra of the industry, but there is obviously much more work to do to educate clients about the benefits of such economic analyses.

The analysis of the historical evolution of FRP in comparison to other structural materials helps to critically analyze the state of FRP development today. Any developer of FRP materials should take pause about the future prospects of the material given its low success between the 1950s and 1970s. However, the current upsurge in use that began with the formation of MDA in 1993, and the Northridge and Kobe earthquakes of 1994 and 1995, is fundamentally different than the former experimental period. During that period, the pioneers were trying to sell not only a product but also a new idea of living. There was no particular market for the material since traditional materials were satisfying demand and FRP offered no particular advantage that the market deemed useful. Today's applications are market driven by perceived or real deficiencies of established materials, particularly in bridge construction. Since the early 1990s, it has become apparent world wide that the bridges built in the post-World War II period are in need of repair, strengthening or replacement. A time-material confluence has occurred because so many bridges were built at the same time. This means that FRP, unlike its introduction in the 1950s over a decade after post-war rebuilding began, is well positioned industrially and knowledge-wise to make a competitive bid to gain market share in the bridge market. This potential market is big enough to have attracted a competitive number of investors and entrepreneurs to develop the material. This creates a dynamic market that results in greater creativity and more intensive research and development to better understand the behavior of the material.

The graph shown in **Figure 6.34** was made in 1993. This graphs seems to be an accurate reflection of what should be expected of the near to mid-term development of FRP materials. It is misleading to the uninformed that substitution should be at the start of the development because this ignores all of the experimentation already made in the first period of development that began in the 1950s.

For the developer who wants to climb this graph line as expediently as possible, it seems wise to study in more detail the failings that occurred in the first period of development, particularly with respect to processing technologies, education, cross-disciplinary engagement and team building, cultural understanding and marketing. In this way, costly mistakes that repeat the errors of the past can be minimized because such mistakes needlessly set back progress made in building up widespread confidence in the material.

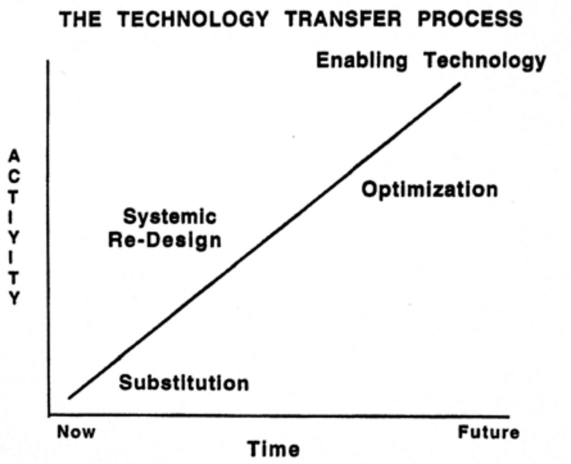

Fig. 6.34: Graph showing expected development of FRP structural forms. (Chambers)

This is indeed a period of transition for FRP materials in civil infrastructure applications. The parallels between the development of FRP materials, aluminum and reinforced concrete should be considered carefully as indicators of FRPs future growth. The historical examples show that FRP can be expected to follow one of two paths. FRP will either:

- Succeed in becoming a so-called conventional material like steel, wood, or reinforced concrete; competing directly against these materials in bridge and building structures.

or

- Become a niche building material like aluminum or plywood, used as secondary building elements like façade panels, window frames, doors, etc. Exceptionally, some special structure will be built for unique situations such as the aluminum semi-monocoque structure of the Media Center at Lord's Cricket Ground in England. (**Appendix A-09, p.A.382, Fig. 41**)

The goal of FRP becoming a mass-market material can only succeed if: the industry succeeds in selling life-cycle cost analysis to clients; architects become interested in learning about the material for building applications; the public is influenced to become more receptive to the more efficient forms of FRP structures, or these forms have to address cultural expectations of what building forms should look like; the construction industry needs to be brought up to speed on how to work with this material; design procedures are made open while the strength of the proprietary systems are gradually eroded over time. The success of FRP as a primary building material will largely depend on how function-integrated building systems can be made competitive against more traditional, multi-layer systems.

Processing technologies, the matrix-fiber bond, and the quality and behavior of adhesive connections all have to be continually improved to meet the objective of FRP becoming a mass-market material. There is vibrant development going on along these lines in the industry. The result is that FRP components can increasingly be made with more complex forms with higher quality and increased production rates, for a lower price. Increased production and reduced prices makes FRP materials economically accessible to a wider range of applications. This means that more minds are applied to the development of the material, which should lead to the development of material-adapted forms.

Finally, if historical precedence is of any value, the developer of FRP materials needs to recognize that many of the most widely recognized developers of material-adapted forms in the past were both designers and fabricators. The commercially successful ones were also good salesmen. Perhaps a study is warranted to determine what were the personal characteristics of single-minded, designer-constructor developers of materials like: William Fairbairn (iron); Saint-Claire Deville and Ferdinand von Zeppelin (aluminum); Joseph Monier, Wayss & Freytag, François Hennebique, Robert Maillart, Eugène Freyssinet, and Eduardo Torroja (reinforced concrete); and Eladio Dieste (reinforced brick).

If it is impractical for the contemporary developer to be both designer and constructor, then they need to form partnerships. The bridge market seems to be developing on its own with all of the necessary capital and knowledge skills to develop FRP conceptual ideas into marketable products. Building construction is more complicated. Recent examples of FRP buildings are designed by teams of architects and boat builders. The use of boat builders is appropriate because they are designer-constructors. They are particularly useful to the development of FRP housing because they already deal intimately with the dynamic demands between form, structure and habitat.

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CONCLUSIONS

07

7.1 The Influences and Form-Finding

This thesis analyzes *why* structural forms have evolved as they have. The objective being to use the knowledge gained from this study to aid the development of material-adapted forms for structural materials today. **Chapter 04** examined various influences on the development of structural form. Those influences are: *Function, Material Properties, Processing Technologies, Connection Technology, Construction Process, Economics, Socio-Political Factors, Knowledge,* and *Technological Thought*. These influences demonstrate that structural form is not the product of material properties alone.

Structural form is not created in a vacuum. The examples used throughout this thesis to demonstrate the development of forms represent forms created for specific functions. Answering the question of why structural forms have developed as they have can be approached on two levels. The first level is technical, and the second has to do with historical context. This thesis principally focuses on the technical aspects of structural development. The contextual approach was employed to analyze the state of the development of fiber reinforced polymer (FRP) materials today in **Chapter 06**.

The developments of Eaton Hodgkinson's 'ideal' cast-iron beam[1] and Robert Stephenson's wrought-iron tubular beam[2] can be analyzed by the technical records available that explain the methods used to arrive at those specific forms. (**Ref. Appendix A-03, p.A.77, Fig. 1 and p.A.100, Fig. 30(b)**) Studies can determine what the creators of new structural forms knew of the material, the limits of processing technologies, and structural theory. The forms themselves can be analyzed for material-adaptedness by examining the relationship between a form, loads conditions, and material properties. However, such an analysis is incomplete without considering whether *structural efficiency* is the primary objective when creating material-adapted form; or if the structural efficiency of a particular Component necessarily means that the System Form is also efficient.

This thesis analyzed the influences individually. Function principally defines the spatial limits that a structure may occupy and the loads to which it will be subject. A Function Pattern can graphically represent these parameters. There is a distinct Function Pattern for each problem. The Function Pattern of the Britannia Bridge demonstrates how historically original patterns can lead to new structural forms. (**Fig. 4.14**) It could be interesting to further explore this notion of patterns to see whether there might exist families of patterns that are associated with certain types of structural solutions. It seems a daunting task, perhaps fruitful, but outside the scope of this project.

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[1] **Ref. Appendix A-03, p.A.101-102**.

[2] **Ref. Appendix A-03, p.A.116-p.A.132**.

Function also defines parameters that can affect the *choice* of materials based on non-structural criteria. The use of stone in Greek temple architecture is such a case. The Greeks used stone because it was more durable than wood. Similarly, the higher material cost of FRP bridge decks, in comparison to a comparable reinforced concrete deck, is justified because FRP is supposed to require less maintenance and last longer.

Non-structural criteria also affect structural form. In the case of multi-story buildings, the floor-to-floor distance must be minimized to maximize the useful space inside a given height limit. This means that beams and slabs are preferable to more structurally efficient structural types like a cable system.

Function integration is also included in the influence of Function. The purpose of function integration is to reduce constructive complexity and increase the efficiency of the building system as a whole. Function integration can either be integral, whereby the structure directly performs a secondary function, or complementary, whereby the structure is adapted to accommodate another function more efficiently. The concept of function integration is important to how the development of material-adapted form is developed.

The relationship between structural form and material properties is not self-evident. This complication stems from the fact that structural form is the combined product of forms that are *structurally appropriate* and *materially appropriate*. Structurally appropriate form, which can perhaps be called the Base Form, is defined by geometry and statics. Such forms can be initially conceived of and analyzed without regard for a particular material. Base Forms are those illustrated in Heino Engel's structural typology annexed in **Appendix A-07**. Wire frame and surface models illustrate them. A material's structural properties will determine whether the material can be suitably applied to make the Base Form. They also govern the proportioning of the Components that comprise the System Form.

Material properties, in combination with a material's processing and constructive attributes, determine Element Form. Element Form is mainly relevant to composite materials, though advances in nanotechnology may make practical to one-day design and construct metallic materials molecule by molecule. In the nineteenth century, some iron founders added wrought iron to cast iron when molten. They thought they were 'reinforcing' the cast iron. All they did was lower the carbon content and make the cast iron more like steel. Perhaps nanotechnology will make it possible to produce an **I**-beam or plate girder with material properties that vary from the flanges to the web without having to physically weld plates of different steel qualities together.

This thesis treated Processing Technologies and Construction Process separately from material properties, even though material properties are intrinsically linked to these influences. Processing and construction are aspects of making form that rely on technology, methodology, and organization. Material properties may define absolute limits of what can be made, but the real limits are set by the limits of the technology and construction methods used. The processing and constructive attributes of a material are subject to change because technology and construction methods can be changed and improved.

This thesis did not analyze the influence of connection technology in detail. Connections are a specialized area of engineering practice and are more material specific than System or Component Form. This thesis focused on the development of Component Form and its lateral relationship to System and Element Form. Connections are special because they have great influence over the overall structural behavior of the System. Connections create inefficiencies in tensile structures because such structures require complicated and often heavy end fittings. The efficiency of such structures is largely dependent on scale. Such issues influence the process of form-finding. The relationship between connection technology and form-finding should be the subject of further study.

Technological Thought, *Knowledge*, *Socio-Political Factors* and *Economics* are influences that define context. The influence of dissatisfaction with an existing form, or a material in a particular application should be added to this list. Together, these influences are the basis for generating Function Patterns; without which there is no enabling purpose to create new forms. Material Properties, Processing Technologies, Connection Technology, and Construction Process all influence the form-finding process, but neither is the root impetus for generating new form. The problem with analyzing historical forms using a technical approach is that analysis begins after the System Form has been determined. This approach fails to take into account why a particular material or System Form is being used. We can answer this question by approaching the original question as a problem of understanding historical context.

Would the Greeks have made stone beams if they had not become successful traders, allowing them the financial means to build their temples? Would Thomas Telford have built the Menaï Suspension Bridge if the Royal Navy had not forbidden the use of an arch? Would he have built the bridge at all if the steam engine had not been invented, which helped lower the price of iron? Would Robert Stephenson have continued to develop the tubular bridge concept if the shareholders of the railroad had not pressured him to get the bridge built as quickly as possible? Would Zeppelin have used plywood to build his rigid airships if a water-resistant, structural adhesive had been available in 1891 rather than 1908?

These questions truly address why a structural form was created in one way versus another. These parameters explain not only why a new form was created, but also why they were developed at a particular time in history. The development of iron in the nineteenth century was the product of a confluence of historical events and technological advances that made iron available in greater quantity and quality, at a lower cost. As the cost went down, the material became economically accessible for a wider range of applications. In turn, more minds were applied to the problem of using iron in the best way to justify its cost. Could the shareholders of the railroad have afforded the quantities of wrought iron used by Stephenson to build the Britannia Bridge if the hot blast furnace had not been invented in 1828, reducing the cost of both cast and wrought iron? Would the early pioneers of FRP housing have been more successful if they had leaned from the experience of the early pioneers of reinforced concrete by adapting the material to the prevailing architectural styles? All of these questions touch upon the subject of context and whether a particular period of history is conducive to the creation of new form or the development of new materials.

The focus of this thesis is on structural form. The questions raised in the preceding paragraphs are somewhat outside the scope of this project. **Chapter 06** began to address these questions because answering them can be useful to developing materials, and thereby new forms. The hypothesis being there is a time and place for certain development, and the study of the historical evolution of materials can help direct efforts for developing materials today. **Appendices A-09 and A-10** provide supporting documentation of this hypothesis. Further research in this direction can be used to create material development tools modeled on the Material Evolutionary Groups of **Appendix A-10**. The number of available materials keeps increasing. Each new material gives data to help refine the characteristics of material evolution defined in **Appendix A-10**. The fact of the matter is that the development of form is integrally linked to historical context and the overall development patterns of the material. These aspects should be further studied.

There is a complex interrelationship between the various influences. This thesis has only begun to examine the mechanisms that link them and how they collectively influence the process of form-finding. The Form-Finding Influence Interaction Model, outlined at the end of **Chapter 04**, presents a basic model for rationally organizing the influences in a step-wise form-finding process. This process is organized by three form-finding phases. The purpose of the first phase is to define Ideal Form. The second phase defines Constructible Form, and the third phase defines Implemented Form.

The Ideal Form phase is divided into two steps, Ideal_1 and Ideal_2. The Ideal_1 step defines System Form. As discussed above, System Form can be conceived of without regard for material. The principle influences on the initial System Form model are the Function Pattern, Knowledge – particularly with respect to statics and system types, and Technological Thought. Heino Engel's structural typology, annexed in **Appendix A-07**, can be a useful tool in this step. Someone should expand Engel's typology should be expanded to specifically include bridges and non-building structures.[3] The product of this step is a wire frame and surface model.

The Ideal_2 Form stage gives materiality to the model. In normal design, this entails choosing a material. To do so, the designer must define suitability criteria to determine he best material for the application. Michael F. Ashby's material selection charts and various material indices can be a powerful tool in this process. Examples of Ashby's method and charts are annexed in **Appendix A-08**. The developer of a particular material will have already pre-selected a material. It would be reasonable that the developers would apply their experience and knowledge of the material to the Ideal_1 stage. However, developers should be cautious not to be blind to the limits of their experience, and the perceptional biases that go along with them.

The objective of Ideal Form form-finding phase is to conceive of the most efficient structural form that will satisfy the requirements of the Function Pattern. Efficiency can be measured in one of two ways. Structural efficiency, whereby the least amount of material is used for a given structural function, is the most common interpretation of efficiency. However, efficiency can also be addressed by considering the relative efficiency of the entire building system, which includes both structural and non-structural building components.

Structural efficiency is achieved by focusing on the influence of a material's structural properties and applying them to the System Form derived in the first step. This step will define the Component Forms of the System, as well as the Element Form. At this stage,

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[3] During this research, I became aware that there is little or no dialogue in either civil engineering or architecture about the role of those professions in the future development of structures and habitat designed for sub-ocean and outer space. Why is that? Will such structures be left to naval and aerospace engineers? Or, is this possibility too far off in the future to consider seriously yet?

issues of how to make, construct or afford the form are not relevant. The purpose of the Ideal Form phase is to identify the preferred form, which best exploits the properties of the material.

Building system efficiency is achieved by function integration. This approach entails that such things like environmental envelopes and building service equipment not be considered construction details but rather an integral part of the Function Pattern. The objective of function integration is to achieve net material reduction in the building system. This may entail that some structural efficiency be lost or more structural material be used. The loss of some structural efficiency should be acceptable if it improves overall building system efficiency and value of the constructed project. The main purpose of integral integration is to improve efficiency of the system by part-count reduction. Further research is needed to establish an economic basis for the limits of function integration. It is necessary to determine whether there is a certain minimum production volume or size of an integrated structural Component that justifies the increased design, tooling and processing costs of an integrated system.

The Constructible Form stage determines whether and how the Ideal Form can be built. The principal influences of this stage are Processing Technologies, Connection Technology, and Construction Process. The objective is to maintain the efficiency of the Ideal Form while adjusting the forms to the limits of current capabilities to process and construct forms using a particular material. This stage does not consider cost.

The single most important influence in determining the Implemented Form is Economics. Economic criteria are complex and do not necessarily translate into low cost. Socio-political factors, non-structural performance parameters, and life-cycle cost analysis are all examples of how the criteria for economic analysis can be defined.

The form-finding model can be used to identify why preferable forms cannot be implemented. Developers can thereby direct their efforts towards removing barriers to building more efficient structures while respecting economic realities.

7.2 Material-Adapted Form and Form-Finding

Material-adapted structural form respects the nature of a material, is optimized for efficiency and economy, and aesthetically expresses these qualities. **Chapter 05** defined the nature of a material to be characterized by its material properties – both structural and non-structural, and its processing and constructability attributes. Material-adapted form is that which is derived from the form-finding process outlined in **Chapter 04** and exhibits the qualities of good structural form defined in **Chapter 05**.

The hypothesis of this thesis is that *material-adapted form is not unilaterally determined by a material's structural properties*. The last section outlined why structural form in general is not defined by a material's structural properties alone. However, this hypothesis can be treated in a more restricted manner by distinguishing the difference between a form that is material-adapted and one this is not.

It was stated in **Chapter 05** that any structure that can be fabricated and does not fail respects the nature of the material. Material-adapted form does not just respect the nature of a material; it exploits it as an integral means of achieving both efficiency and economy in the constructed project. It can be said that the nature of the material is specific to the properties of the material. This interpretation would counter the hypothesis if it were not for the fact that the processing and constructive attributes of a material are not solely defined by a material's properties. Processing attributes are dependent on the technologies that exist to manipulate materials into form. These technologies depend on the development of separate materials and technology. Constructive attributes are similarly dependent upon the equipment, methods and organization of construction to place the structural material in its proper position and form. The nature of a material is not a static concept for these reasons; and is not therefore defined solely by material properties, structural or otherwise.

Integrating the concept of material-adapted form into the form-finding model reveals that the line would blur between all three phases of the form-finding process. As a matter of practice, the rigidity of the model inadequately takes into account the fluidity of the creative process. When Eduardo Torroja was iterating a final design solution for the Madrid Racecourse[4] in a matter of minutes, it can be taken for granted that he drew upon his cumulative experience to rapidly reject and refine his concept. (**Fig. 5.3**) This experience included issues of construction and economy. In so skipping ahead while still in the Ideal Form phase, the designer can avoid fundamental problems when moving ahead to detailed design in both the Constructible and Implemented phases. The mind will not ignore its experience. In reality, there is a creative interplay between the different influences of each form-finding phase. One way to account for this fluidity in the process is to integrate technological thought into the model. This requires more detailed study of the writings and thoughts of engineers, architects and, if possible, builders. The profiles of the types of persons to target for further study should be those who were known to be master designers *and* builders. This group could include the English industrialist William Fairbairn, the German concrete construction firm Wayss & Freytag, French reinforced concrete builder François Hennebique, Swiss engineer Robert Maillart, Italian engineer Pier Luigi Nervi, Spanish engineer Eduardo Torroja, and Uruguayan engineer Eladio Dieste. Such designers will have a more comprehensive understanding of the nature of a material; and how that nature, particularly its processing and constructive attributes, can be integrated into the conceptual design process.

Conversely, the rigidity of the form-finding model can be useful to avoid discounting certain forms by jumping to economic issues in the Ideal stage. Nervi recommended that structural efficiency should take precedence and that if this is achieved, economy will follow. This may depend on the skill of the designers, fabricators and builders. But if the intention is to develop the best forms, then economics needs to be momentarily put aside. Using this model rigidly allows the fullest freedom to conceive of the most efficient form. If that form is not constructible or economical, the model becomes a tool for identifying the reasons why. The model allows problems limiting the use of a form to be identified so that barriers to making the Ideal Form an Implemented Form can be overcome.

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[4] **Ref. p110**.

7.3 For the Developer of Materials

The developer of materials can use the knowledge presented in this thesis to better understand the progress made in material development today. **Chapter 06** examined the state of development of fiber reinforced polymer (FRP) materials. This chapter showed there are similarities between the development of FRP today and that of other structural materials in the past. This information can be used to tailor research and development efforts to take into account historical precedent and contemporary trends. If the futuristic forms of early FRP housing models were rejected in the 1960s even though they were material-adapted uses of the material, then it should be questioned whether such forms should be tried again in the near future. Instead of trying to make society adapt to a material and different style of living, perhaps it is more prudent to adapt FRP to more familiar forms while preserving the particular advantages and attributes of the material. A thorough study might reveal that FRP is not suitable for primary building Components and the focus of development should be on secondary Components as is the case with aluminum.

The idea that materials must transcend a substitutional phase before material-adapted forms are developed is a misleading concept. Even when a material is used substitutionally, the nature of that material is respected on the Component and Detail level. Plywood, aluminum, FRP, iron, steel, and reinforced concrete were all used in adapted ways when they first became available. Plywood and FRP were both specifically created to overcome deficiencies of other materials. Wrought iron was used in tension members from antiquity. Cast iron's use in arch forms was more adapted than its use in beams.

When materials are substituted, often after an initial development, it is because the material was perceived to have superior qualities than the material it replaced. This was the case with the development of the cast-iron mill beam in England at the turn of the nineteenth century – it was considered superior to timber because of its fire resistance. Cast iron was surely more expensive than timber, however the higher cost could be justified as an investment against damages to the mill and equipment should a fire occur.

Substitution can be considered an important application of a relatively new material because it allows designers and builders to learn about the nature of the material by using the forms of known materials and applications as a standard of comparison. However, it does not follow that the pioneering users of new materials did not appreciate the nature and potential of those materials, as evidenced by reinforced concrete, plywood, aluminum, and FRP. In the case of aluminum, its high cost early in its history prohibited its use in structural applications. FRP was hindered by limited development of resins and processing technologies, but its potential forms and applications did not go unrecognized. J.E. Gordon, an English materials scientist who was instrumental in the development of glass fibers for FRP structures, saw the immediate possibility of using GFRP to make stressed skin airplane wings.

The conservatism of the construction industry is often cited as a hindrance to the introduction of new materials into the market. The slowness of change is perhaps not so much a cultural problem as much as a reluctance to retrain laborers, and invest in new equipment and construction methods to adapt to what is a relatively unknown material. The failure of FRP housing in the 1950s and 60s demonstrates that this attitude is sensible. Perhaps this is why early pioneers of materials are often both designers and builders. With respect to the failure of FRP housing, perhaps too the conservatism was not with the construction industry at large, but with the conservatism of architects who were slow to adapt to the new material as they were with iron in the nineteenth century. Clearly, the developer of materials needs to actively support efforts – perhaps through an industry association – to educated clients, the public, government agencies, designers, builders, educators, and, most importantly, students. The more minds that are applied to solving the problems of FRP, and creating new ones, the more likely it is that material-adapted forms will develop and be implemented.

7.4 Implications for the Development of Engineering Design Process and Evaluation

7.4.1 Higher Level Problem Definition

This thesis presents several new tools for developing engineering design methodology. These tools are the Function Pattern, the Form Hierarchy (System, Component, Element and Detail), and the Form Types (Ideal, Constructible and Implemented). The key contribution these tools make is there usefulness in achieving a higher-level definition of structural engineering design problems. The relationship between these three tools is outlined in the Form-Finding Influence Interaction Model.

7.4.2 Practical Implications

The practical usefulness of this thesis is threefold. First, the Function Pattern concept is not only a useful ordering concept for the numerate design parameters that define an engineering problem, but it can also be translated into a graphical design tool for computer based conceptual design. Currently, engineering software is largely limited in its capabilities to aid conceptual design. Rather, software today is principally good only for analysis. The Function Pattern could provide a graphical based design methodology.

Computer program’s written for conceptual design will have to incorporate aspects of artificial intelligence. Subrata Dasgupta’s book *Technology and Creativity* (1996) offers a good introduction to this area of computational development. This thesis contributes to this field by its original analysis of the history of structural engineering in the case studies. These case studies can be researched in further detail, and others made, to help construct a model of the design process that, importantly, starts out with some level of residual knowledge of why certain structural forms are chosen over others. Most importantly, these case studies begin to explore the importance of historical context to explaining why structural forms have evolved as they have.

The second practical implication is the usefulness of the Form-Finding Influence Interaction Model to the design process. This model’s rigid organization emphasizes the development of high-quality structures because it devalues the influence of technological or economic limitations during conceptual design. For both designers and developers, this model can be used to identify what the limitations actually are (usually a combination of technology and economy) to the implementation of ideal forms.

Third, the Evolutionary Group Model is a potentially powerful tool for material developers. A more refined understanding of the characteristics of material evolution can aid in decisions about the allocation of research and development resources.

Furthermore, for the developer, my interpretation of the role of substitution in material development has important implications with respect to the way this phase is viewed and utilized. Perhaps the conclusion that this phase is useful and, perhaps, critical to the development of new structural materials will convince developers to undertake a concerted effort to use substitution intentionally. Substitution can be used to learn more about the material, and gain the trust of clients and the wider design community. To reiterate, knowledge of material evolutionary characteristics can inform the developer of when a proper time might be to exploit the positive aspects of the substitution phase more effectively.

I suppose that some kind of equivalent model of my Form-Finding Model could be made to apply to architectural design using much of the same terminology. Though aesthetics and symbolic meaning can and should be an intrinsic part of engineering design, it is not as prominent as it is in architecture. However, such issues are already accounted for in the model under the Function influence. As described in **Chapter 04**, aesthetics, program and spatial definition are all Functional parameters. Therefore, there is some applicability of this model to the architectural design process. The most promising application of this model however would be when the architect and engineer are working as a team before conceptual design begins. Synergies between the architectural and engineering requirements of a project can be best addressed this way. A builders and material fabricators should be brought in at least as soon as the Ideal phase is complete. Such a team approach is conducive to function integrated design. Lip service is given today to inter-disciplinary design teams, however such teams are still rare in practice. The testament to why such an approach is desirable is perhaps best summed by Felix Candela when he stated, “The only way to be an artist is this difficult specialty of building is to be your own contractor.” This statement clearly is evocative of the need for the concept of “master builder” to be rekindled in the design and construction industry.

7.4.3 Pedagogical Implications

The concept of the Function Pattern and the Form-Finding Model can both be used as tools of academic training. These tools provide a structure for defining and solving problems in a rational way. The Function Pattern could perhaps be developed into a three-dimensional modeling tool that has the potential to influence design thinking today as J.N.L. Durand did in the early nineteenth century when he introduced a grid-based design methodology. This methodology emphasized space rather than mass, which was characteristic of the beaux arts tradition of design.

The Form-Finding Model can similarly influence the way students solve problems and the development of their design thinking. In some ways this model represents the current pedagogical format of architectural design education today. Typical design students will start a project conceptually and imagine the ideal form. Then they will (hopefully) develop a constructible form. Unfortunately, design projects rarely reach the stage of implemented form.

For engineering students, the Form-Finding Model could be used to emphasize the importance of conceptual design, a welcome respite for the heavy emphasis on analysis, at least in American universities. This method forces a more concerted effort to understand structural systems and the properties of structural materials; which in turn forces the student to better understand the difference between forms that are generated by simple structural mechanics and those dependent upon material properties. It is the hope of this author that the Form Finding Model could in some way be used as a basis from which to structure interdisciplinary design teams for students, however this author is not optimistic that such a system is viable as long as students are (and must be) graded as individuals.

Finally, I hope that this thesis could inspire the need to make the history of engineering a fundamental aspect of engineering and architectural education today. A great disservice is being done to society by not adequately educating young engineers about the accomplishments, and failures, of the past. In not doing so, we are creating a situation where we are either trying to continually reinvent the wheel, or worse, increasing the risk of repeating failures that could have been avoided with even the most rudimentary knowledge of history. For the architects, an engineering history could emphasize the role that materials play in the development of architectural form and building types.