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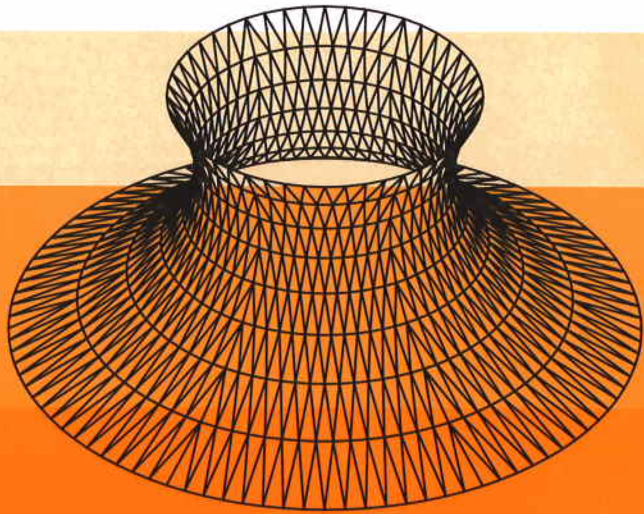

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INNOVATIVE TIMBER CONSTRUCTIONS

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ABSTRACT

The research undertaken in the EPFL's Timber Construction Laboratory aims both to question in depth the relationship between engineering sciences and architectural conception and to expose new facets of this relationship. The IBOIS is firmly integrated in the Civil Engineering Institute, as well as being involved in architecture through the setting up of a workshop for architecture masters students.

Timber construction has a great future in the face of global sustainable development challenges. The advantages are well-known as far as low energy consumption for the production of building components (planks, boards, beams, etc.) is concerned. Savings in time and energy consumption are also noticeable in timber structure assembly and dismantling processes. But the challenges of sustainable development also concern the issue of architectural form. How can one introduce a process of formal and technological innovation in a perspective of sustainability?

Keywords: *Timber construction, spatial shell structures*

1. INTRODUCTION

Over the last two centuries the predomination, first of steel, then reinforced concrete, within research and applications in the field of civil engineering and materials science has underlined the huge gap in our knowledge of timber as a structural material to be engineered. Much intuitive know-how of our builder and carpenter predecessors up to and during the 18th century has been lost with the rise of the 'Ingénieur des Ponts et Chaussées'. Meantime, the use of timber as a construction material by modern-day engineers and architects has barely evolved, their having a priori accorded it a lower level of importance than for steel and concrete.

The IBOIS research laboratory proposes to investigate and develop a new family of timber constructions based on principles of origami folded plate structures and textile fabrics. In this context, and within the scope of several case studies, one of the core objectives is to create an innovative structural system with concise aesthetic, spatial and structural qualities. Thus, the research addresses important challenges at the frontiers of the field of architecture and civil engineering.

Research in architecture, architectural composition, production, and even construction processes remains closely linked to the personal design process of a specific architect, while the architect's freedom of expression as an artist is, by definition respected as inherent to the creative process. This epistemological framework makes research in architecture different and difficult to accept for disciplines more clearly rooted in either technical or social sciences cultures. In general, research in architecture is not primarily intended to give importance to the technique that is applied. Truly interdisciplinary research approaches linking architecture with civil engineering remain difficult. Technical considerations are very often considered as an almost neutral set of knowledge, which do not, or should not affect in a determinate manner the initial creative design process of a given architect. Technique, construction methods and ultimately civil engineering and static considerations are seen as almost unwelcome ingredients in a certain number of cases. Those supposedly neutral technical considerations are more often than not tacked on at a belated stage in the design process, compromising the truly interdisciplinary and fundamental quality that such research approaches could aspire to. Even certain very celebrated iconic buildings, such as the Guggenheim Museum in Bilbao by Frank O. Gehry, or the Olympic Stadium in Bejing by Herzog & De Meuron, show that formalism and the structural approach have been pushed back to the status of secondary issues. The aesthetic quality of the newly generated structures and forms discussed within this paper are considered to be of significant influence both in establishing those forms on a building scale and in establishing their acceptance on a social scale. A detailed understanding of textile techniques is essential both to appreciating the aesthetic qualities of the novel construction materials resulting from our research and to proposing novel wood-based structures that are both feasible and useful for society. This research will offer numerous opportunities for architectural, civil engineering and small scale applications.

2. TOWARDS A NEW FAMILY OF STRUCTURES

The application of origami and textiles principles to building scale timber derived structures is in itself an act of invention, since civil engineering structures have first and foremost to satisfy as robust structures – beams, columns, construction elements that are constituent parts of a bigger integral unit – in order to achieve their load-bearing quality. Our society is not used to thinking about such major civil engineering infrastructure and equipment using expressions such as ‘origami’, ‘textile’ or ‘timber’. The word ‘textile’ usually carries an underlying connotation of softness, and the word “origami” an underlying connotation of fragility, which does not match the general context of engineering structures. At present, ‘origami’ and ‘textile’ techniques have a large range of applications and interpretations, but there have been no previous attempts to connect their qualities and production technologies to the scale of timber construction. The invention of structural timber fabric requires both a vision of the future and an understanding of the past to inspire an integrated planning process, where craft, technique, aesthetic and structural engineering’s aspects come together as they did just before the revolutionary “Age of Enlightenment”, but this time using contemporary engineering methods and tools.

Applying origami principles and textiles to building scale is also an act of invention within the field of architecture and specific contemporary architectural approaches. The raw resource in question has innate qualities (such as smoothness) that can also satisfy aesthetic demands and conceptual qualities that architects value. The emerging tools in digital architecture, design software, and the digital drawing tool seen as an instrument to conceive architecture, have opened the way for broader applications of digital technology, also those of a technical nature. Together the emerging technical advances that now lie within attainable horizons, render feasible the integration of textile principles, textile technologies and fabrications systems in ways that were unthinkable only a few years ago.

The environmental arguments for enlarging the possible uses of renewable timber resources are undeniable. Society’s burgeoning awareness of the urgent need to define/use/consume materials that are sustainable has become an important influence in timber construction’s renewed economic importance in recent years. Environmental considerations are set to restore or establish the legitimate use of timber in our cities’ constructions on a scale unprecedented since many centuries. We are only now discovering that techniques ranging from friction-welding, knitting, weaving and even origami can be applied to timber on a building scale. The application of such techniques can radically expand timber’s range of technical and aesthetic attributes. Just as such techniques promise to lead to the invention of timber products fit for novel purpose, society is becoming both culturally and economically ready to accept timber as a construction material which is no longer marginal.

Timber construction research asks for cross cultural and interdisciplinary approaches borrowed from architecture, civil engineering and material science. But the timber construction industry itself has remained a particularly conservative and traditional one. It is only when examined at a closer perspective than is traditionally associated with its present day uses in the construction industry that timber reveals its surprisingly close connections to other textile materials and its vast potential for the application of textile techniques: Timber can be classified as both a soft material and a viscous material having smooth properties. It is subject to "creep", almost as a liquid material. All timber is basically composed of a multitude of cellulose fibres. These smooth fibres are flexible, allowing curvature.

Until now, the capacity to impose curvature for example on glued laminated timber beams, has not lead to a broader interpretation of that property for timber, but in fact its implications are profound. Indeed timber has the capacity to adopt and to retain any given form. The application of textile principles to timber constructions at a building scale allows us to take advantage of the possibility to curve timber elements. Timber is on the point of becoming amenable to the realization of highly complex woven structural systems. In such systems, an important number of interactions of pieces of relatively small size constitute robust large scale structures, satisfying efficiency of production and safety considerations. They can combine aesthetic qualities such lightness and light transmission and functional qualities such as rigidity or flexibility. This radically new generation of timber construction is set to change the face of timber construction as an architectural form, both taking it away from the classical image of traditional architecture and improving the use of timber in constructions of contemporary character. The old-fashioned image of timber as the material of the 'chalet' and related vernacular architecture could soon give way to a contemporary interpretation of the use of timber in our constructions and establish it as a hightech material playing a central role in a society concerned by sustainability.

From the combination of the 'ingredients' "timber", "textile", "fabric" and "civil engineering structure" may emerge a generation of structures which has literally no equivalent or even counterpart today. It is possible, (even probable), that in addition, other presently unforeseen applications for new "virtual" structures will emerge from the data we can collect from actually producing the prototypes of such structures at building scale. This area of research could lead to new forms of furniture, carpentry, design applications in general, and have implications for other timber related applications such as floor finishings, separating walls etc.

If at this point in time most of the specific applications must remain as pure conjecture, the initial, interdependent steps of designing and physically conceiving hitherto inexistent forms of woven timber constructions can only stimulate further developments of the timber industries and the use of timber in the construction sector.

On a wider level, the investigations of the IBOIS laboratory contribute to a more profound understanding of spatial structures in general and set new precedents for cooperative interaction between the architects and engineers who will analyze those structures.

3. POTENTIAL IMPACTS

3.1. Promoting a renewable material by appealing design

With the current discussion on the change of the global climate in mind, it is more than obvious that there is a need to change our social behaviour in many ways. Alternative energy (re-) sources need to be discovered and made accessible and a lower consumption of energy needs to be achieved. Here the production and energy consumption of building structures play an important role, which makes timber, as a renewable resource, an interesting building material that should be used more frequently as such. However, environmentally conscious behaviour cannot be achieved by obtrusion only. In order for more people to invest in environmentally friendly products and materials, these have to become more attractive as well. In the past, this was a problem for the popularity of sustainable architecture, which was mainly realized with timber as the building material. It has always had a rustic, primitive and alternative associations, which, though attractive to some, was repellent to many other potential clients. In order to access this later group, design needs to be treated as a serious criterion. The design of contemporary and appealing architecture with timber is now both necessary and possible.

3.2. Buildings with a higher disaster resistance

Traditional design and development of large structures are largely based on the concepts of stiffness and efficiency. They are substantially aimed at minimizing the bending of the structural components and at generating structures that can be characterized as rigid and inflexible, avoiding elasticity. Disastrous failures of conventional structures (for instance under conditions of seismic activity or unusually strong wind forces), are reason enough to suggest we must rethink these paradigms of stiffness and efficiency and try to strike a new path in the conception of structures. Here, textile techniques, especially the way they are deployed in basketry, provide interesting perspectives. They offer high-resolution networks, composed of many individual components. Together they form an entity, which offers the advantage that the failure of singular elements does not trigger the failure of the entire system.

3.3. Establish new timber derived products and applications in construction

In fills and claddings, ready-to-build-systems can be already be developed from the basic principles described in this proposal. In addition alternative architecture applications exist but have not yet been taken further for industrial applications; As an example, one might envisage the industrial production of new classes of timber derived products such as weaved timber separating walls.

3.4. Improve and expand the uses of timber for public buildings

Timber structures made out of simple rectilinear elements have essentially defined timber construction and carpentry for centuries. With the development of new digital tools, timber construction could be transformed allowing its introduction into a wide range of new applications. As shown by the use of the various digital tools under development, other potentially physically achievable geometries and constructions may emerge first as virtual representations. Such developments introduce a new range of civil engineering challenges of interest in the field of timber construction. To date, structural analysis has not been as widely applied to timber construction as it has to steel or concrete construction. Now, the use of planar structural elements made out of timber-derived products and of curved linear elements, such as those described below, will help to introduce timber in constructions such as public buildings where architectural and aesthetic considerations are deemed to be of strong cultural importance.

4. FROM ORIGAMI TO FREE-FORM STRUCTURES

It is interesting to note the variability of Origami structures, as shown [1]. Their architectural, mathematical and engineering concerns are treated by the IBOIS team. (Fig.1). This level of investigation is a precursor to more complex forms being made out of timber block panels. Origami-inspired new timber construction has also been the subject of another publication [2].

We believe further possible developments could be of interest. Instead of using folded geometric patterns, as previously proposed, Gilles Gouaty and Ivo Stotz [3] of the IBOIS laboratory have developed a digital modeling interface, which can be seen as a geometric tool to develop a wide range of folded and also free-form structures. The goal of this particular area of our research is to create files as a data base for construction purposes. Such structural descriptions need to be mathematically "clean", meaning that they work exclusively with discrete elements (that can be exported for reasons of dimensioning and automated production - the so-called "digital chain").

The Iterative Function Systems (IFS) used to design complex wood structures present the advantage that they allow for the exportation of discrete geometrical surfaces, lines or volumes. By using IFS, no constant curvature will be produced, in contrast to the use of splines (data interpolation functions) where such curvature may occur. This research has been described in more detail in the IASS journal under the title 'Iterative geometric design for architecture' [4]. In this context the IBOIS research 'gets real' by not just proposing construction production and building methods for timber construction but also and foremost by exploring the mechanical and structural observations and optimization processes of those timber constructions [see also 4].

5. FROM TIMBER RIB SHELLS TO WOVEN STRUCTURES

Over the past years substantial research on rib shells structures has been carried out by the IBOIS Laboratory. Former and current projects include the works of Claudio Pirazzi [5] and Johannes Natterer [6] and deal with rib shell structures based on geodesic lines.

In order to optimise grids of timber rib shells in the face of the bending stress of the boards due to initial curvature, the GEOS software [Geodesic line modelar] was developed at the Ecole Polytechnique Fédérale of Lausanne between 2002 and 2005.

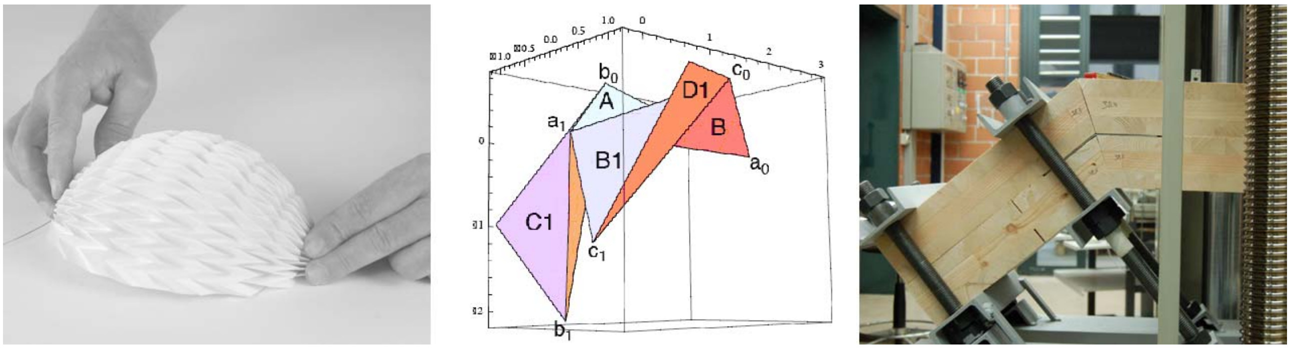

Figure 1. *Origami fold; mathematical description; test advice*

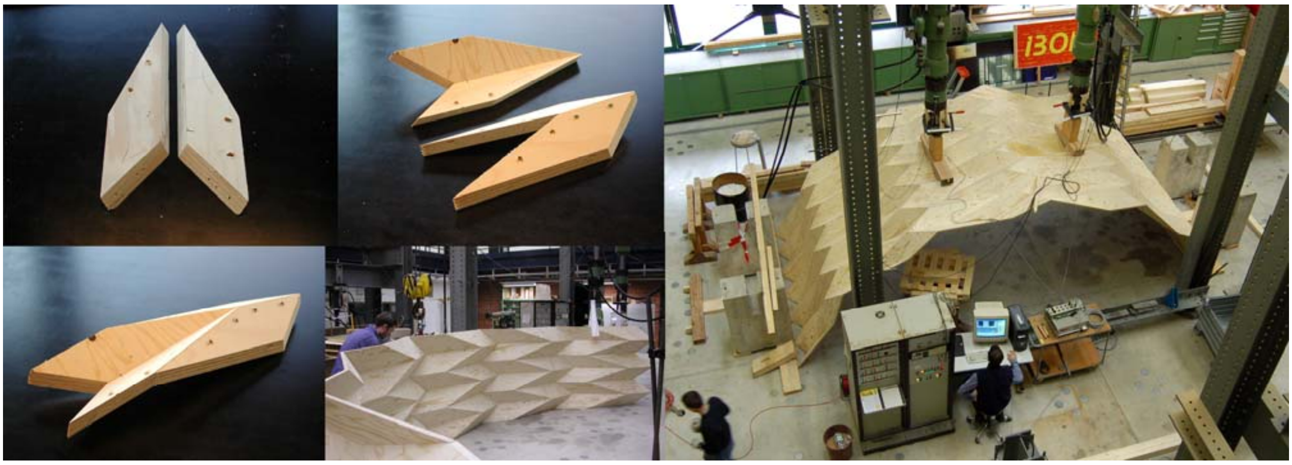

Figure 2. *Prefabricated timber element; real scale prototype*

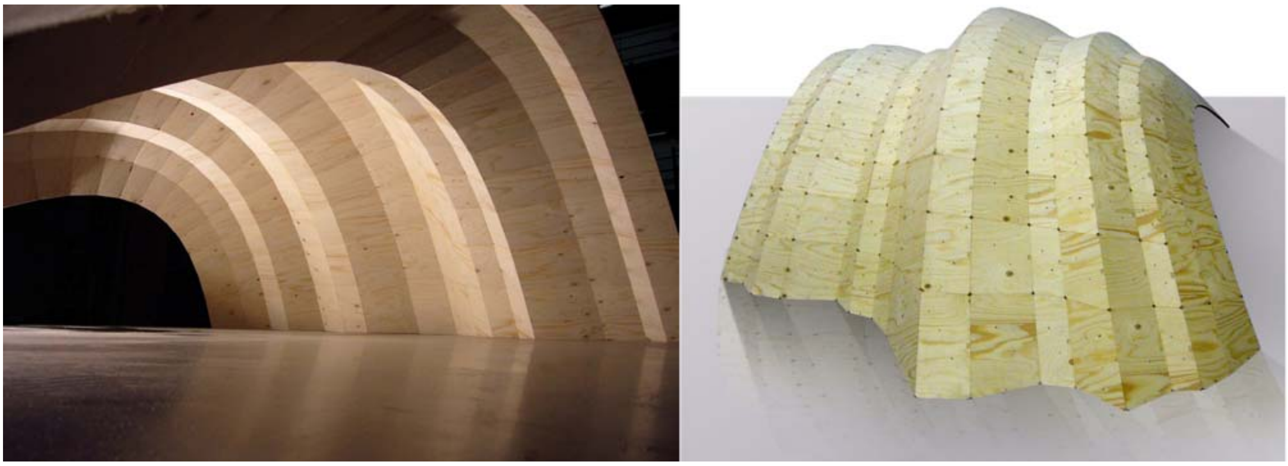

Figure 3 . *Generated spatial structure made out of block timber panels*

During its application testing stages, in collaboration with the IBOIS laboratory, an automatically produced large-scale rib shell structure prototype was generated to demonstrated the correct working of the software. The mechanical analysis of the rib shell structure has since been addressed and the bending behaviour for nailed or screwed rib shell structures is now known. We have shown that shell forms can support more intensive bending moments than traditional wood structures, encouraging us to believe it should be feasible to realise structures inspired by weaving techniques at the building scale. Stacked planks, - as employed in rib shell structures - show certain analogies to textile structures, and may be interpreted as quasi-woven fabrics. Timber rib shells are composed by multilayer elements and those elements are curved. Both of these characteristics can also be found in textile structures. The development of rib shell structures towards woven structures can be seen as a direct link: As more precise knowledge of the bending behaviours for nailed or screwed rib shell structures becomes available, we may expect to see new woven shell forms or structural timber fabrics emerge which can support more intensive bending moments. This should lead to the practical realization of such structures inspired by specific weaving techniques.

The expression ‘textile’ is used here not in a literal way as in architecture where the terms textiles and bashes are employed. The proposed research instead focuses on the structure of textiles and their woven aspects in general. Textile structures have long attracted the interest of architects, but mainly because of their aesthetic properties. Until now, their structural characteristics and particularities have been almost completely neglected. With the recently increasing interest in the use of textile techniques in architectural applications, there has arisen the motivation for an in-depth investigation of textile principles and structures in order to improve the ways they are applied in buildings. Projects like Shigeru Ban’s Pompidou Centre in Metz or the railway station in Worb, by Swiss architect Smarch, are just two examples among many that illustrate the growing relevance of fabrics as references for both structural and aesthetic qualities in architecture.

Unfortunately, there are also numerous recent examples that betray a lack of true understanding of how textiles work. Most are trying to reproduce a superficial metaphor of textiles instead. The research undertaken at the IBOIS shows how to identify feasible adaptations of textile techniques to wood construction and how to go beyond the examples realized so far.

It also identifies consequences of using different textiles techniques in structural elements for large-scale buildings. It addresses the question of how to translate them into building structures without betraying the basic principles which underlie their desirable attributes. For instance, in fabrics, as well as in basketry, the coherence of the yarn elements is governed by friction. The question arises as to whether textile principles can transform building-scale timber into something with new properties, something that is more than merely a literal metaphor of weaving. The consequences of such an approach might result in something that is not immediately recognized as a textile structure, yet adapts its logic in the most stringent way. This could be achieved by realizing the normally curved geometry of yarns in fabric, in an abstract way, with non-curved planar elements.

Nowadays, digital processes are a common means of architectural morphogenesis. Nevertheless, their usage often presently results in projects that neglect actual materiality in one way or another. Evolutionary processes inform seamless digital matter whose properties have no relation to those of real materials. Physical matter is treated as a passive compound, a mere means to an end, and form is obtruded upon it by subtractive techniques such as milling.

Almost any material can be used, depending on which texture effect is desired. Unit-based processes and techniques can improve the relationship between the digital and physical properties, as they can be connected to the real world's necessity for assembly. However, the materiality of the units or elements plays only a passive role.

We consider the material's physical properties as an active parameter for the software development. The already mentioned modeller', published under the title: "IFS Modelling for Architecture, New Solutions for the Design and the Construction of Complex Shapes" and developed at the IBOIS is a reference point from which we intend to evolve new software related to Structural Timber Fabrics. The aim is to develop a programme that allows for digital modelling which matches the real material behaviour and deformation - and can therefore be of use for the planning of Structural Timber Fabric. The digital models are based on mathematical descriptions of the fabric structures. These mathematical descriptions are highly complex and can be achieved by the means of discrete geometry. Therefore, to successfully execute this part of the work, inputs from mathematics and mechanical engineering are essential. In the process it allows us to examine to which degree a certain technique of assembly and the active use of materiality have influence on the geometry of the resulting construct. It also shows the importance of physical modelling and the advantages this continues to offer. The first result derived from this approach is the so-called 'Textile Module', which is generated by interbraiding two strands of timber. This use of a particular technique of assembly, together with the specific material properties, leads towards a structurally efficient construct. Where the material plays an active role instead of a passive one, its geometry is automatically generated during the construction iteration process.

Towards a Digital Materiality: Despite the important role that physical models play in our approach, the use of digital tools will continue to be indispensable for exploring the potential of the discovered phenomena. Furthermore, the aim of developing a marketable product demands the integration of digital planning and production tools at this stage. This is a crucial point; current software doesn't have the capacity to simulate material deformation. This limitation highlights the areas in which further developments are necessary in the future in order to work dynamically with matter. Minimising and eventually eliminating such detected limitations is a highly desirable aim. Inclusion of the dynamic potential and constraints of materiality into digital processing and planning will result in an exceptionally powerful tool.

The structural analysis of woven wood structures necessitates a stage of preliminary investigations. In order to establish proper analytical models of such structures, a clear understanding of their geometry is required. In general, the intention is to build such woven structures out of initially plane timber derived block panels. During the weaving process, those initially planar panels will be deformed in order to match curved or better "weaved" forms. The imposed deformations on these panels will lead to initial stresses provoked by bending and torsion moments, which will appear in the panels. Specific questions arise such as: Which radius is required? Which curvature can be accepted? Those questions will be addressed by an empirical approach on ready to build prototype structures and their close observation in terms of geometry and material properties. The necessary subsequent structural investigations should become apparent from this type of preliminary observations.

The scale factor has essential bearing on all scientific and human research. In our own research, we have been confronted with various questions related to such scale jumps. We wish to know more about such scale factors and how they can affect the spatial, but also the mechanical behaviour of structures. We know at present that larger structures are more subject to flexibility and dynamic sensibility while proceeding with those scale jumps. We are able to define a specific, dynamic calculation for a specific structure at a given scale. But we have not yet been able to define parameters, which describe the optimization of these structures through different scales while keeping every proportion the same. And we do not yet know the underlying rules determining how these sensibilities occur or when they occur.

The study of this fascinating topic involves a very precise recording of scale jumps related to structure and how they behave in a mechanical way. In other words, interwoven fabrics form complex combinations, which interact in ways that can be described with mathematical precision. At present, we know only that the description of these interactions changes in function of the scale of the structure.

The development of calculation methods in order to determine the structural stability of these highly complex constructs is one of the most important goals of the IBOIS. Therefore it is necessary to accompany the architectural and conceptual parts of our projects with a structural analysis.

Figure 4. *Studio Weinand: textiles applied on building scale*

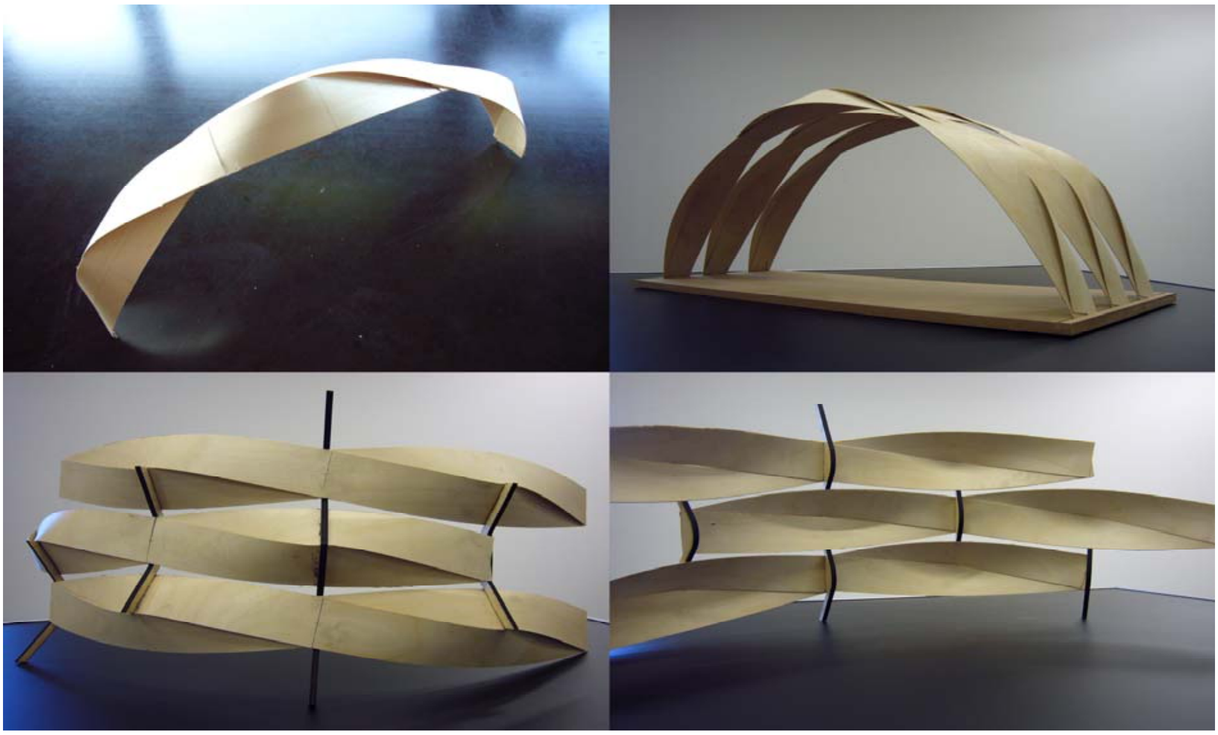

Figure 5. *Textile module and their combinations on building scale*

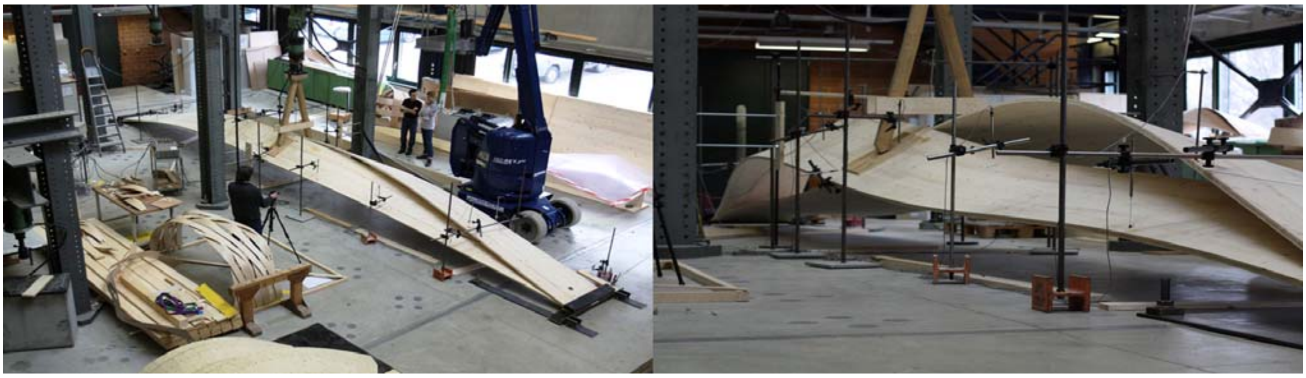

Figure 6. *Real scale testing on textile modules*

As we attempt to optimise prototype structures for specific parameters, the first set of observations that need to be made are systematic comparisons between the initial structure and deformed structure for every given structural proposal or geometry. Geometrical and mechanical observations need to be established. The deformation process creates a specific stress situation, which can be described as initial stress. Those stresses can be determined by means of computer simulation (Finite element Modelling) where the deformation process is modelled. The initial stress situation can be established by means of measures taken directly on the physical prototype by stress captures. Once the initial stress situation is known, various load cases can be performed giving more insight into the structural performance of a given woven timber fabric. The interaction of the curved elements occurs in such a way that the final global rigidity of the newly composed structure increases. In terms of global structural deformation this is an advantage. But when it comes to absorb high loads in terms of global structural failure such as earthquakes for instance, the initial structural quality designated as smooth smoothness still represent an advantage since the initial powerful impulse of the earthquake will absorbed by that smoothness.

In our pilot studies of prototypes, very original structural behaviours have been observed, such as an increase of the rigidity of a given woven section while applying a load to it, or the section's inertia increases during the loading process because of the structure's capacity to be deformed. Such observations open very exciting perspectives for the utility of structural optimization processes.

6. CONCLUSION

The novel timber fabrics we envisage at IBOIS are composed of a multitude of small interconnecting structural elements. Such iterative structures can be said to develop a sort of 'social' behaviour, in the sense that in case of the failure of the weakest element this failure will not provoke the collapse of the structure as a whole since the load of the weakest element will be carried by adjacent elements. As a consequence, woven timber structures and origami folded plated structures show great potential to have a higher security factor (which is yet to be precisely determined) than traditional timber carpentry where the failure of one element, may lead to the collapse of the structure. The implications and study of these phenomena need to be further explored.

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