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Low Carbon Pathways for Structural Design

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Abstract

To avoid an increase in greenhouse gas emissions, a depletion of resources, and waste accumulation, structural engineers have a major role to play in low carbon structural design. For example, cement-based materials represent one-third of all materials extracted each year [1]. This paper offers three pathways for lowering the embodied carbon of building structures – the emissions related to material extraction, production, transport, construction, maintenance and demolition – through the lens of three case studies of building structures in Switzerland. The first pathway focuses on the structural scale by reducing material intensities in terms of material use per unit of floor area. The second pathway focuses on the material scale by lowering the impact of the materials themselves through the choices of the materials typically used in structures. The third pathway focuses on potential changes to current construction practices by (re-)introducing reuse strategies in the building sector. A simplified version of Life Cycle Assessment (LCA) is used to evaluate each Swiss case study compared to current practice. The material quantities are collected from literature, architectural drawings, Bill of Quantities (BoQ), and Building Information Models (BIM). This research illustrates the challenges and opportunities of three pathways for low carbon structural design: the optimization of material efficiency, the use of low-carbon materials, and the reuse of structural elements from other demolition sites.

Keywords: embodied carbon, structural design, construction, LCA, environmental impacts, optimization, materials, reuse

1. Introduction

Buildings' whole life cycle emissions are not only comprised of *operational* carbon due to their use phase, but also *embodied* carbon due to the rest of their life cycle: material extraction, transport to the site, construction, and demolition. While architects often take measures to reduce the operational carbon, engineers are often involved at a later stage of the design process when decisions that could reduce the embodied carbon of a building cannot be taken anymore. Indeed, the structural component encompasses the majority of a building's material weight [2, 3]. This paper summarizes the feedback received from a wide range of stakeholders – architects, structural engineers, policy makers, rating-scheme developers, to establish three pathways, which work best when combined, for low carbon structural design.

2. Problem Statement and methodology

Using case studies of Swiss building structures, this paper discusses the challenges and opportunities of three pathways for lowering the embodied carbon in structures. The question addressed to designers is: how low can we go? While LCA has been around for decades [4], this assessment method did not reach its intended goal to reduce the environmental impacts of the building sector as it is time consuming, costly, and often requires an LCA expert. In order to offer straightforward strategies to reduce the impact of structural design projects, this paper offers a transparent methodology for which only two key variables are required: Structural Material Quantities (SMQ, expressed in kg/m^2 when normalized by floor area) and Embodied Carbon Coefficients (ECC, expressed in kg_{CO2e}/kg). If we exclude operational emissions, the Global Warming Potential of a structure (GWP, expressed in kg_{CO2e}/m^2) can be calculated by multiplying these two key variables, as illustrated in Equation 1.

$$\sum_{i=1}^{N} [SMQ_i \times ECC_i] = GWP \qquad \text{Equation 1}$$

where:

i a particular component or material in the building structure i = 1, 2, 3, etc., N
SMQ_i Structural Material Quantities (kg_m/m^2)
ECC_i Embodied Carbon Coefficients (kg_{CO2e}/kg)
GWP Global Warming Potential (kg_{CO2e}/m^2)

The low carbon pathways are derived from each element in Equation 1: simultaneously lowering the SMQs by optimizing material usage in structures, lowering the ECCs by choosing low carbon materials, and lowering the GWP by reusing already existing structures or structural elements.

2. Low Carbon Pathways

Three case studies of building structures in Switzerland illustrate the three pathways related to the SMQ (2.1), the ECC (2.2), and the GWP (2.3) respectively in this paper. The best strategy is to combine all three pathways. The embodied carbon emissions of the three Swiss buildings compared to those of conventional buildings are discussed in section 3.

2.1. Structural optimization

The first pathway is structural optimization. Historical examples of optimized structures in Switzerland can be found in the works of Heinz Isler or Robert Maillart. A parametric model of conventional concrete buildings [5] recently demonstrated that most of the material quantities in typical buildings come from the slab. Therefore, the Block Research Group (BRG) at ETH Zurich designed a rib-stiffened funicular floor slab [6] to show how material savings can reduce the embodied carbon of buildings.

The first case study discussed in this paper is the NEST HiLo building to be constructed in Dübendorf, Switzerland (Figure 1), as a research and demonstration platform for innovative building technologies developed at ETH Zurich. The building integrates BRG's innovative floor system with a cable-net and fabric formed roof shell. Thin funicular vaulting inspired by the Guastavino Tile Vaulting system [5] as well as structural ribs save over 70% of materials and 50% of carbon compared to conventional concrete slabs [7]. Future work includes digitally fabricating them [8] in order to avoid formwork.

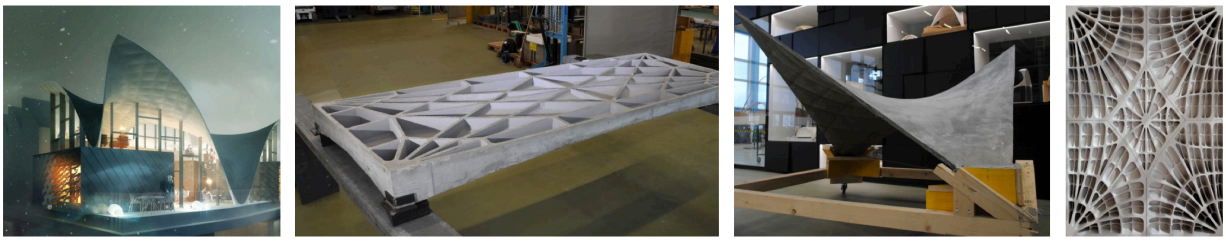

Figure 1: NEST HiLo in Dübendorf, Switzerland: a) building, b) floor system, c) roof shell, [9] d) digital fabrication [8]

2.2. Material choices

The second pathway lowers the ECC by choosing low carbon materials. The most commonly used materials in building structures are concrete, steel, and timber.

As concrete is the most used construction material and cement is the most carbon intensive component of concrete, current research redefines cement [1, 10]. One example is the replacement of ordinary Portland cement with volcanic ash, as shown by Kupwade-Patil *et al.* [10]; another is the development by Scrivener *et al.* [1] of a new type of cement based on a blend of limestone and low-grade calcined clay. This Limestone Calcined Clay Cement (LC3) can reduce CO_2 emissions by up to 30%. No capital-intensive modifications are needed to existing cement plants so that LC3 is also cost effective, as shown in the Europe Climate Foundation (ECF) project.

Alternative materials can also be considered, such as rammed earth, which has a significantly lower ECC compared to concrete [11]. Swiss architects Herzog and de Meuron consulted rammed earth specialist Martin Rauch for the Ricola Herb Center in Laufen, Switzerland, for example [12].

Timber, when sourced from a sustainable forest, can be a renewable construction material absorbing carbon emissions during the growth of trees and therefore turning buildings into 'carbon sinks'. The second case study analyzed in this paper is the seven-story high Tamedia Office Building in Zurich, Switzerland (Figure 2), designed by Japanese architect Shigeru Ban [13]. The structure uses 2000 m^3 of prefabricated elements in spruce wood with no additional steel reinforcements, saving over 70% of CO_2 equivalent emissions compared to similar office buildings.

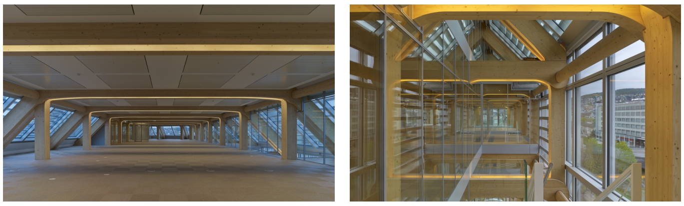

Figure 2: Tamedia Office Building by Shigeru Ban in Zurich, Switzerland [13]

2.3. Reuse

Results show that the embodied carbon of buildings can be an order of magnitude lower than the average of existing buildings by combining the two first pathways: using low carbon materials and structurally efficient systems [14]. A third pathway can be added by applying circular economy principles to the built environment.

This third way to lower the GWP of structures all together is reusing waste materials. For example, the Structural Xploration Lab (SXL) designed a demountable gridshell after testing the stiffness of thrown-away skis [15]. Rather than starting from the typology and form to define the materials and components, Brutting [16] optimizes structures starting from a given stock of components. My last case study is the Cabanon Project (Figure 3) in Lausanne, Switzerland [17]. The art pavilion reused structural elements from the dismantling of the International Olympic Committee (IOC) headquarters, bringing down the embodied carbon of the new pavilion design by up to 90% compared to conventional construction.

Figure 3: The Cabanon Project in Lausanne, Switzerland: a) IOC headquarters, b) art pavilion, c) plans of pavilion [18]

3. Discussion

As illustrated in Figure 4, the embodied carbon of building structures can be successfully lowered by following three pathways: lowering the SMQ by designing material efficient structures; lowering the ECC by choosing low carbon materials; lowering the GWP all together by reusing waste materials. The savings in carbon emissions are based on similar buildings in the database of embodied Quantity outputs (deQo), used for benchmarking embodied carbon in building structures [19]. The three pathways should be integrated rather than applied separately in a particular design, in order for a structural designer to actively reduce carbon emissions of buildings. International initiatives are underway to develop a uniform methodology to quantify savings in embodied carbon of buildings [20].

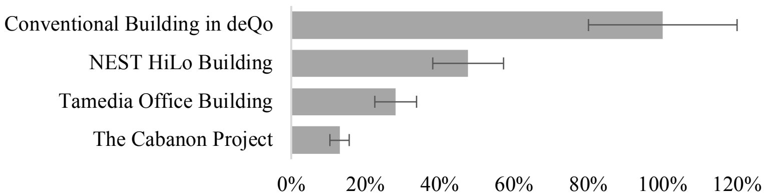

Figure 4: GWP of Swiss case studies relative to conventional buildings in deQo, including uncertainty

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