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LIFE CYCLE ASSESSMENT OF A POST-TENSIONED TIMBER FRAME IN COMPARISON TO A REINFORCED CONCRETE FRAME FOR TALL BUILDINGS

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Abstract
This paper summarises a recently conducted project to investigate the sustainability of high-rise timber buildings. In particular, an innovative post-tensioned timber frame structure using glued laminated timber was compared to a functionally equivalent traditional reinforced concrete frame by means of a cradle-to-gate Life Cycle Assessment (LCA). Further, the two structures were compared with regard to costs and time for the construction. The assessment showed that the post-tensioned timber frame structure contributes about 44% less on greenhouse gas emissions compared to the traditional reinforced concrete structure. Additional performed analysis estimating the construction costs and construction time showed the great potential when using timber in comparison to reinforced concrete.

Keywords:
Life-cycle assessment; Post-tensioned timber; Reinforced concrete; Costs; Construction time; Greenhouse gas emissions

1 INTRODUCTION

Over the past decade, the design industry has been increasingly looking towards timber as a building material for the construction of tall buildings as timber has great material properties and at the same time can be considered an attractive material for green building construction. Investors and owners place a greater importance on sustainability in building construction and operation, as buildings are a major contributor to greenhouse gas emissions [1].

Since timber is considered as a renewable resource and forests supplying timber can offer a natural carbon sink, the use of timber in building construction can positively contribute to sustainable building practices.

In this context, an innovative post-beam construction made of glued laminated (glulam) timber was developed at ETH Zurich, namely the post-tensioned timber frame [2], see Fig. 1. A glulam column is being connected to glulam beams using a straight steel tendon. No additional steel elements are required. The high degree of the systems' pre-fabrication leads to higher and controlled construction quality, to an easy construction on site, to a reduced construction time and to an enhanced safety on site. The frame is able to carry gravity loads and horizontal loads, therefore no additional load-bearing elements are required for the building, leading to a great amount of flexibility for the users.

Fig. 1: Post-tensioned timber frame.

A structure of a newly built 3-storey office building at ETH Zürich (*ETH House of Natural Resources*) has recently been built with the post-tensioned timber structure made of glulam using hardwood

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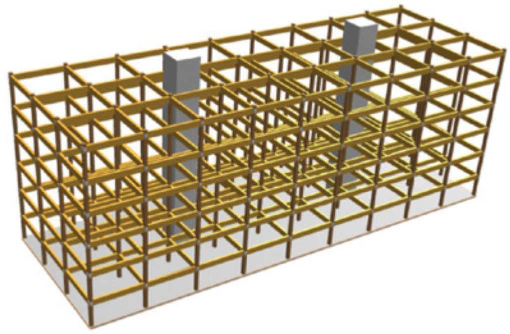
(*ash* and *beech*) and softwood (*spruce*), see Fig. 1. The hardwood reinforcement is needed to strengthen the supports, where stresses perpendicular to the grain occur.

The post-tensioned timber frame structure is a possible timber construction, which allows building tall timber buildings in a very efficient way. In this context, a feasibility study was performed within a master project thesis at ETH Zurich investigating the possibility to build tall timber buildings with this structure and further to study the potential and benefits of this structure when used for tall buildings.



In case of the timber building:
Timber columns: *ash*, GL48h, 400 x 400 mm^2
Timber beams: *spruce*, GL24h, 200 x 600 mm^2

In case of the concrete building:
Concrete columns: C80/95, Ø = 450 mm

Note: Given are the maximum dimensions of the ground floor; column size is stepwise arranged, decreaes with buildings` height.

Fig. 2: Schematic sketch of the skeleton system made of post-tensioned timber.

In a first step, the preliminary structural design of two exemplary buildings was performed. Based on this design, a life cycle assessment concentrating on the structural elements as well as estimations on costs and construction time were conducted. This paper summarises the main results of this investigation.

2 HIGH-RISE BUILDINGS IN A SKELETON SYSTEM FROM CONCRETE AND TIMBER

A preliminary structural design for two high-rise buildings has been performed. One building uses the post-tensioned timber frame as structural elements. The second building is constructed as a traditional reinforced concrete building. In order to reasonably compare the two buildings with each other, they were planned with exactly the same function and size. The boundary of the buildings is as follows:

- 90 x 24 x 57 in [m] (length x width x height) including storeys for building technology
- 17 storeys above ground
- 2 storeys below ground for parking, storage and building technology
- Height per storey: 3.35 m
- Reference building area: ~ 41’000 m^2
- Foundation on gravel (15 m thickness) above multiple layers of marl and molasse

Both buildings were planned as a skeleton system being a very flexible structure allowing a fast and easy change in use.

The buildings were designed as an office building located close to Basel (CH). The design of the building considers the new fire regulations in Switzerland [3]. Further, the design for earthquakes was performed for the seismic risk zone Z2, building class 2, subsoil class D and a behaviour coefficient q = 3 according to SIA 261 and SIA 262 [4,5].

2.1 Structural system and materials

The design of the buildings was performed according to the Swiss design Standards SIA. Required dimensions and material properties are the outcome of the structural design of the two buildings. However, it should be noted that the design is of preliminary state meaning that the final dimensions and material properties might be improved for the final design.

The building using the post-tensioned timber frame as the structure is consequently planned with timber floor elements with additional mass and insulation to fulfil the serviceability limit state design requirements, e.g. vibration and sound insulation. The floors in the concrete building are consequently planned as traditional reinforced concrete floors.

Both buildings are horizontally braced with a reinforced concrete core with equal dimensions and functional units, although the timber building might allow for a reduction of the core dimensions due to the lower self-weight in comparison to the concrete building.

Dimensions and material properties of both buildings are the result from the structural design, see Fig. 2. Using timber for the structural frame elements leads to a strong reduction of building weight. In our particular case, the timber building can be built on a spread foundation and thus does not need any pile foundation. Whereas the concrete building is only possible to realise with a pile foundation due to its rather high self-weight.

2.2 Life-cycle assessment

Definition of the system and data collection

The environmental advantages of using timber as a structural element in construction have been discussed in various research endeavours [6,7,8]. In [6] and [7], it was proven that the substitution of a concrete with a timber building in a Swedish context can lead to reduction of the climate impact potential between 50% and 200%, considering also the option to capture CO_2 in the timber material. John and Habert examined the environmental impact of timber and concrete buildings in a Swiss context and affirmed that timber outperforms concrete in terms of environmental behaviour [9]. However, the

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buildings examined in the latter study were medium-rise (3 to 4 stories high). In the current research, the goal was to study the environmental performance in the case of the high-rise building described above through a comparison of a timber building and a conventional reinforced concrete building.

The two buildings with the same structural system but different materials were analysed using a Life Cycle Assessment (LCA) in order to identify the main contributors to carbon emissions. LCA is a tool used to trace the environmental impacts of a product throughout its life cycle from raw material acquisition to production, use, maintenance and final disposal [10,11]. In this study, the boundaries of the system correspond to a cradle-to-gate analysis, encompassing all processes up to (and including) the construction of the building. The CO_2 emissions were calculated based on the method IPCC 2007 (GWP 100a) [12] with the use of OpenLCA 1.4.2 and the Ecoinvent v2.2 database [13].

In order to be able to compare the environmental impact of the two buildings, the structural floor system of the building with the same gross floor area and the same structural and thermal performance was used as the functional unit.

Furthermore, the following assumptions were made for the purposes of this study:

- The life cycle of the buildings was assumed 60 years. All main construction materials were assumed to have a service life of 60 years [9].
- The use of insulation of the same thickness in the roof and the basement as well as the provision of the same openings in both buildings ensure the same thermal performance, and thus a similar energy consumption during the use phase.
- The transportation distance from the manufacturing to the construction site was assumed to 30 km for concrete, since it is locally produced, and 150 km for steel, which is usually transported over longer distances. With respect to timber, two scenarios were tested: (1) in the first case, timber was transported by truck inside Switzerland for 150 km while in the second one, it was imported from abroad. In this case, a transportation distance of 2500 km (which is about the distance from Swedish forests to Switzerland) was assumed, either by (2) train or by (3) truck. No transportation distance for the common materials was accounted for.
- The Life Cycle Inventory for the structural elements for both buildings is shown in Table 1. Under the category "other materials" belong all non-structural elements, such as floating screed, insulation material, gypsum plasterboard or bitumen sealing, among others. Steel includes the reinforcement required in both buildings as well as the pre-stressed tendons in the case of the timber one.

Results and discussion

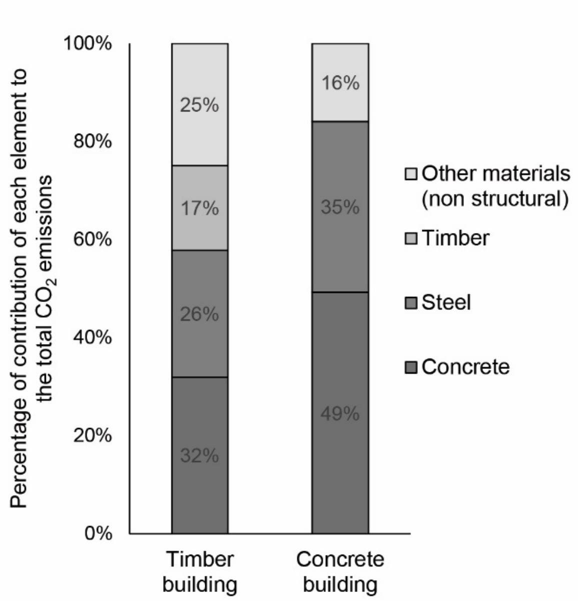

Fig. 3: Contribution of structural elements to CO_2 emissions of the timber and concrete building.

A comparison of the LCA of the two buildings is presented in Fig. 3. No transportation is included in the values of the figure. The results show that the manufacturing phase of timber products demands a very low amount of energy relative to reinforced concrete. In both buildings, reinforced concrete plays a determining role in the environmental performance of the building; concrete and steel together contribute to 84% of the total CO_2 emissions of the concrete building and 58% of the timber one. In the timber building, the largest part of the emissions is attributed to the construction of the concrete core and the

Material/Element	Unit	Timber building	Concrete building
Concrete	[m^3]	6'241	17'464
Steel	[t]	833	1'991
Timber	[m^3]	4'990	0
Other materials (non structural)	[t]	5'304	5'476

Table 1. Life Cycle Inventory for the Timber and Concrete Building.

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basement. Among the other non-structural materials, floating screed has the highest contribution to the total greenhouse gas emissions (16% for the timber building versus 9% for the concrete one). Table 2 summarizes the CO_2 emissions of the two buildings.

	Timber building	Concrete building
Total t CO_2 eq.	4'774	8'478
t CO_2 eq./m^2	0.116	0.207
	56%	100%

Table 2. CO_2 emissions for the two buildings.

With respect to transportation, it is observed that, with the exception of timber sourced from distant forests and imported by truck, transportation of the structural elements does not contribute significantly to the greenhouse gas emissions of the construction (Fig. 4). Regarding the transportation of timber over long distances, the railway network should be preferred. Further, it is recommended to use local timber (if the strength class is locally available) and avoid long distance transportation especially by truck.

It should be mentioned here that many building certification schemes prescribe specific requirements for the use of timber. For example, Minergie-Eco® in Switzerland excludes the use of wood from non-European forests without a FSC (Forest Stewardship Council) or PEFC (Program for the Endorsement of Forest Certification schemes) label.

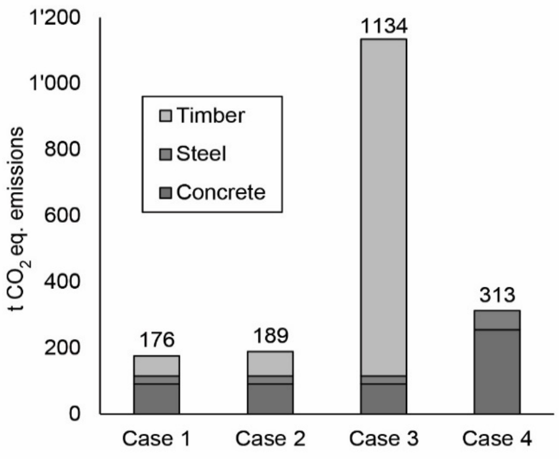

Fig. 4: Impact of transportation of structural elements for the different scenarios (Case 1: Timber building – 150 km by truck, Case 2: Timber building – 2500 km by train, Case 3: Timber building – 2500 km by truck, Case 4: Concrete building).

These labels ensure that wood is sourced from sustainable forestry. In addition, the use of local timber is in alignment with the requirements of Minergie-Eco®, which promotes the use of materials with reduced environmental impact in order to achieve a long life cycle, flexibility in the use and possibility of deconstruction (eco-bau, 2011) [14].

As mentioned before, the LCA performed in this study does not account for the end-of-life of the two buildings. End-of-life scenarios entail considerable uncertainties since they attempt to predict future events, where the fate of the demolished materials is highly uncertain [15]. The end of life of the timber structure can involve either disposal of timber, use as fuel for electricity generation or disassembly and reuse of the timber elements. It should be noted that timber systems for prefabrication and disassembly (two main advantages of the analysed post-tensioned timber frame) allow for reuse of the material and a more resource-efficient product life cycle than typical demolition and down cycling. On the other hand, the concrete frame at the end of the building life cycle can be either demolished and landfilled or recycled. Further work could be directed toward studying the impact of the different end-of-life scenarios to the total CO_2 emissions of the two buildings.

An additional benefit of timber, which was not captured by the present LCA, is its property to temporarily store carbon. However, this is outside the scope of this paper, since it largely depends on the origin of the wood and the growth of the wood markets and there is no consensus with respect to the carbon sequestration credits [16].

2.3 Additional analysis

Cost estimation for load-bearing structure

The costs of the two buildings were estimated on the basis of several quotations of companies offering their products on the Swiss market and using the EAK Swiss cost catalogue [17]. Further, the experience gained from the construction of the post-tensioned timber frame of the *ETH House of Natural resources* supported this work and led finally to a reasonable cost estimation, as reasonable as it could be.

It was found that, given the above described circumstances, the building using the post-tensioned timber structure is about 4% cheaper than a building built with a traditional reinforced concrete structure. This can mainly be explained by the fact that timber has excellent strength to weight ratios which makes it possible to realise the building only with a spread foundation without expensive (money and time) piles. However, it should also be noted that when only the costs of the skeleton system (above ground) is compared, the concrete structure is about 11% cheaper than the post-tensioned timber system, which is in line with earlier studies [18].

As a consequence, buildings using the post-tensioned timber frame structure and thus an eco-friendly material, are not a-priori more expensive than traditional reinforced concrete buildings. The comparison of the costs should include the whole

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picture of a building. However, it should also be noted that a building generally built with timber needs a more detailed planning in an earlier planning phase. Further, high quality detailing and exact implementation on site are very important when building with timber.

Construction time

The two buildings under investigation were further analysed with regard to the construction time. It was assumed that both structural systems are built using a high degree of pre-fabrication allowing for high-quality certified production and a rapid erecting progress. The time for the construction of the structural system built with traditional reinforced concrete was estimated to be about two years considering the documented experience gained from different buildings in Switzerland, namely Roche Bau 1, ETH House of natural Resources, and Aquila-Pratteln.

Since the timber building can be constructed without pile foundation and further without any on-site concreting (e.g. of the floors) except for the core, the construction time of the timber structure can be reduced enormously. It was found that the timber building can be handed over to the building owner in the order of 5 months earlier than the concrete building. However, the core from concrete limits the construction time of the timber building. If the core of the timber building is realised in, e.g., cross-laminated timber (CLT) the construction time of the timber building could be further reduced.

3 CONCLUSION

The paper shows a comparable analysis of two high-rise buildings using a skeleton system from timber (post-tensioned timber frame structure) and traditional reinforced concrete. Both buildings were designed as functionally equivalent in order to determine a most reasonable comparison. On the basis of a preliminary structural design of the building a cradle-to-gate Life Cycle Assessment (LCA) was performed. The LCA showed that the post-tensioned timber frame structure contributes about 44% less on greenhouse gas emissions compared to the traditional reinforced concrete structure. Additionally, it was found that for our particular case the costs of the timber building are in the same range as for the concrete building. This can in particular be addressed to the foundation systems; the concrete building needs pile foundation whereas the timber building can be realised with a spread foundation.

It could further be shown that the timber building can be constructed much faster due to the high degree of pre-fabrication, which is typical for timber buildings.

4 ACKNOWLEDGMENTS

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