Timber-concrete hybrid innovations

A framework to evaluate economical and technical factors for the construction market

VITO LORENZO ZACCARO
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Vito Lorenzo Zaccaro

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ABSTRACT

Nowadays, the focus of the construction market is on sustainability aspects, for which purpose, the employment of wood seems promising. Nevertheless, in countries having high potentiality like Sweden, the timber construction market finds difficulties in growing. The reason lies in the lack of standards for design and industrialization and on the strong competition of the concrete industry. The timber-concrete hybrid solution is presented in this study as a solution beneficial for both the timber and the concrete markets: the former would benefit of a pulling action towards standardization and larger market, while the latter would fulfil the environment-friendly requirements and better differentiate in the competitive landscape.

Therefore, the objective of this thesis is to provide a framework to evaluate innovations in construction market, highlighting the characteristic issues related to the matching of timber and concrete constructions, and detecting the main economic and technical factors to help in the decision-making process. This framework will help to organize and evaluate all the information and the boundary conditions about the introduction of a concrete-timber hybrid construction solution, which eventually would enhance the timber construction market itself through a preliminary association with concrete market.

Firstly, some consideration on the market areas and on the general perceptions towards the timber construction are presented; then, the focus is moved onto the dynamics of concrete and timber supply chains, highlighting similarities, diversities, and possible reciprocal benefits, to finally detect the market indicators to be considered for a decision-making path related to the timber-concrete hybrid construction.

From the technical side, a conceptual design is proposed, considering the industrialization of such hybrid solution. Annex A shows how standardization and modularity of the products would enable compatibility and interchangeability between timber and concrete, on account of the open system within the construction market. Annex B displays a schematic picture of how the exploitation of timber and concrete‘ properties, with the industrialization of these two materials, can be best employed for a hybrid building. A preliminary technical evaluation of the timber-concrete hybrid is carried out by dividing the building into modular units and focusing on the main systems (horizontal loadbearing system, vertical loadbearing system, external envelope, inner partitions), while making consideration on structural design, fire protection, building technology details, building service systems integration, construction plan, and costs.

The innovations within the construction market are often hindered by the fear to undertake a high-risk project. The proposed framework allows to increase the awareness on the general factors to be evaluated, and to undertake a gradual adoption of the “new” timber construction solution. The key points underlying the whole timber-concrete hybrid problem are standardization and modularity, necessary for a quality-oriented production. Further studies need to be carried out with an applicative intent: application of the general framework to real cases and pilot projects; automatic tools for the design and construction optimization including economic and technical factors; innovative and original hybrid solutions, which better exploit the timber-concrete synergy.

Keywords: hybrid construction, timber, concrete, standardisation, modularity, construction market
PREFACE

This master thesis has been carried out at KTH Department of Civil and Architectural Engineering, Division of Building Materials, in Stockholm.

I would like to thank my supervisors Prof. Magnus Wålinder and Dr. Andreas Falk at KTH Department of Civil and Architectural Engineering, Division of Building Materials for all their support throughout this work, for being open to my idea from the very beginning, and letting me work independently.

I would like to thank everyone that has provided me with information and guidance throughout this work. Finally, I will always be grateful to my family and their infinite support, trust, and fondness, as well as to my friends for their unconditional aid.

Stockholm, June 2017

Vito Lorenzo Zaccaro
LIST OF ABBREVIATIONS

3DNP  3 dimensional nail plates
API   Adoption process of innovation
CLT   Cross laminated timber
EPC   Engineering procurement and construction
ETA   European technical approvals
EWP   Engineering wood product
FAO   Food and Agriculture Organization (of the United Nations)
FRC   Fibre reinforced concrete
GFRC  Glass fibre reinforced concrete
IEQ   Indoor environment quality
LCA   Life cycle assessment
LLRS  Lateral load resisting systems
LVL   Laminated veneer lumber
NFRC  Natural fibre reinforced concrete
OSB   Oriented strand board
PNF   Processed natural fibers
SCA   Selection criteria approach
SCM   Supplementary cementitious materials
SFRC  Steel fibre reinforced concrete
UNF   Unprocessed natural fibers
VAPs  Value-added products
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1. Introduction

1.1. Background

Nowadays, the focus of building construction is on sustainability aspects. The building sector is responsible for 50% of the resources humans take from nature and 25-40% of all energy used (UNEP, 2003). There are of course possibilities to improve the built environment, by exploiting the resources better. One of these is the employment of wood in construction, where conditions make this use reasonable and convenient. Nevertheless, in countries like Sweden, where the employment of wood in construction has all the prerequisites for an improvement of the built environment, timber buildings find difficulties in growing on the market.

To enlarge the timber construction market, know-how, common standards, and norms are required, as well as a strong industrialization practice from the manufacturers, standard procedures in the supply chain, and an input from the government or other authorities. In addition, there is the strong competition of the concrete industry, which for many years has led the building construction market, thanks to the routine, strong assets, and networking within both public and private entities; however, nowadays concrete industry has to face new challenges, such as eco-friendly standards and people’s perception of sustainability and cosiness of the building.

In fact, increasing the use of timber into construction projects would improve the management of the knowledge, which is fundamental in the dynamic and complex construction environment. Cross (1998) defines “knowledge management” as the “discipline of creating a thriving work and learning environment that fosters the continuous creation, aggregation, use and re-use of both organizational and personal knowledge in the pursuit of new business value”. The implementation of the knowledge management highly determines the longevity of the business of construction, which is usually highly regulated through many standards, codes and guidelines that make the processes repetitive and similar from one project to another. For the case of the timber construction, technologies, templates, and technical standards should still be established; this could be done through a preliminary association with the already strong knowledge management of the concrete construction business (Anumba and Pulsifer, 2010).

To summarize, developing a concrete-timber construction solution represents a difficult decision-making process involving several and diverse stakeholders, contexts, and technical issues. Therefore, it is needed a methodology to organize and evaluate all the information and the boundary conditions regarding the industrialized housing in general, and the concrete-timber hybrid construction solution in particular.

1.2. Aim and objectives

The objective of this thesis is to provide a framework to evaluate economical and technical factors for concrete-timber innovations on the construction market. Such framework is meant to highlight the characteristic issues related to the matching of timber and concrete constructions and to answer the following main questions:
• What are the main economic and technical factors to consider in order to exploit the advantages of two different materials like concrete and timber and obtain the best synergy from them?
• How is it possible to enable the compatibility between two different materials like concrete and timber?
• How to increase the use of a “new” material like timber within the construction market?

These questions are aimed to incentivize a concrete-timber hybrid solution on the construction market, with the secondary purpose to enhance the timber construction market itself through a preliminary association with concrete market.

1.3. Scope and limitations

The conducted study is qualitative in its nature; therefore, it becomes important to have multiple sources of evidence to verify its validity, which can be defined as employment of the right method in order to achieve relevant results; this is done by describing the data used and how they have been processed. (Yin, 1994). Data have been collected from documents (drawings, handbooks, brochures, proceedings) and through direct observations (insights, perceptions and dialogs with concrete and timber market representatives), to be afterwards processed and mapped. Therefore, this study has construct validity because it is well structured and coherent from the inside, considering that all the inputs have been processed according to a structured methodology, in order to obtain coherent results.

Moreover, the present study is generalizable, but could be too loose-fit when applied to a specific case; however, the presupposition of “evaluating an innovation” justifies this aspect, since the purpose of this research is to provide a framework and guidelines to a not yet well-defined construction situation. External validity is achieved thanks to the possibility to apply the method or the model to the external real world and at the same time to generalize the findings beyond the immediate case study. Finally, to achieve reliability, it would be necessary to measure in what extent the procedure suggested here gives the same result when applied to real cases; but such actual cases are still to be realized.
2. Method

2.1. Type of study

According to Meredith (1998), “It is not possible to conduct and analyse data in research without considering and being aware of the biases due to the researcher’s background and the subjectivity of the researcher”. This research conveys a background of construction and quality management in building engineering and is inspired by the reflection “What is the role of the Building Engineer compared to architects, structural engineer, energy engineers? His role is to manage, coordinate, and optimize various aspects of the built environment, such as structural design, thermodynamics, aesthetics and so on. It is about dealing with the big frame assuring the holistic perspective and the quality of the result”.

The approach to the construction case is top-down: creating a framework for timber-concrete hybrid solutions that can be polished and better defined for particular cases, contrarily to the current practice in timber construction, where particular and exclusive solutions are studied for each case (see “Treet” in Norway or the pilot project “Tall Wood” in Vancouver), preventing somehow the large-scale diffusion of timber constructions.

This study has been conducted according to the holistic approach, in both the sense of knowledge of the construction world (construction management, building materials, structural engineering, energy engineering, IEQ, economics) and the sense of diversification in the kinds of researches (technical research and analysis, empirical knowledge and insights, interviews). The information has been collected from:

- Handbooks, ETA, normative
- Brochures of producers, researches on the state of art
- Conversations with professors, producers and experts of the various sectors

2.2. Methodology

In the literature, there are several frameworks attempting to identify the major factors that influence the success and the performance of the construction market. For example, it is possible to mention the thirteen factors identified by Lin and Shen, (2010) which include e.g. projects, clients, facilitators, participants, team dynamics, techniques, post occupancy evaluation, post project evaluation, and so on. Another example is the “Integrated construction project selection process” which attempts to treat together and interconnect the criteria related to the project success and the project selection, considering them as parts of a unique management process (Shokri-Ghasabeh, Chileshe and Zillante, 2010).

However, these key performance indicators (KPI) have been considered problematic for various reasons (Kagioglou et al., 2001):

- little indication from a business point of view;
- lack of a holistic perspective and connection among the different indicators;
- omission of “innovation and learning perspective”.

The method adopted is a combination of two pre-existing models (Figure 1). The first one is the “Adoption process of innovation (API) in the construction industry” (Entrop and Dewulf, 2010), which proposes a
decision-making process and the adoption of new solutions and techniques within the engineering procurement and construction (EPC) market. The timber-concrete hybrid buildings represent an innovation in the common construction routine: although the materials and the techniques employed have already existed for a long time, common practices for their matching and compatibility should be further explored.

The other model is the “Selection criteria approach (SCA)” (Fregonara et al., 2013) which allows the adoption of a holistic approach when designing an optimal construction solution, by considering different aspects related to the built environment and taking contributions from several research areas usually separated from each other.

![Diagram: Concept of Timber-Concrete Hybrid](image)

**Figure 1.** Method adopted: combination of API and SCA approaches (Entrop and Dewulf, 2010; Fregonara et al., 2013).

3. Literature review

3.1. Demonstrating the need

3.1.1. Insights

The timber-concrete hybrid solution derives first from a convenience reasoning: it can be considered as a solution for short/middle term future and a starting point to enlarge the market of timber construction, and at the same time to give the possibility to the concrete industry to change and softly adapt itself to a new
construction market. This insight has been first confirmed by freely talking to various experts in both timber and concrete markets, including the manager of an international concrete company.

On one hand, the advantages for the timber construction market would be a beneficial pulling action by the bigger concrete market, and a path towards the standardization of processes and normative in the footsteps of the concrete standards. On the other hand, the advantages for the concrete construction market would be increasing the attention towards the environment-friendly legislation and common sensibility, avoiding fees and taxes, and enabling a market strategy by providing a unique construction solution and starting the production in a green field. Therefore, keeping in mind the lean construction perspective, the key points to pursue for the timber-concrete hybrid solution are the exploitation of the materials’ properties and products from a technical point of view, and the incentive to a flexible and fast open system on the construction market.

3.1.2. The innovation capabilities

Toole et al. (2010) demonstrated how the need for innovation has been undervalued within large EPC industries, essentially because of organizational factors. However, there is an indirect link between investment in innovation and improved business performance, implying the possibility of higher profit margins. The main barriers to innovation are due to:

- the focus of many organizations on optimizing the current value system rather than pursuing more radical, systemic improvements (Hamel, 2006);
- the lack of mechanisms for implementing new ideas (Sawhney and Wolcott, 2004);
- the lack of economies of scale;
- the lack of financial cushion and the process interdependency of many separate firms each trying to maximize individual profits (LePatner, 2007).

On the contrary, the characteristics that promote innovation are an effective inter-organizational management and the collaboration among diverse firms to achieve a common goal. A successful innovation process can be achieved by following four key steps, which would enable a continuous learning process (Bernstein, 1998):

1) generalization or conceptualization of an idea
2) development and production of the new technology
3) transfer of knowledge
4) subsequent application to solving problems

Finally, the innovation in construction market should be evaluated in terms of overall value obtained, according to a large-scale economy perspective, rather than the usual performance and profit drivers that the firms are used to (Dikmen et al., 2005).

3.2. Feasibility study and outline financial

3.2.1. Market area

Since the concrete construction market is spread everywhere worldwide, here the focus is on the areas where timber construction market has potential to develop. According to Food and Agriculture Organization’s statistics on the Forestry production and trade (1992-2013) (Figure 2 and Figure 3), the highest share of
production of wooden building materials (e.g. hardboards, fibreboards, chips and particles boards) is registered in Europe (23% with 19 million tonnes) and America (57,1%), especially in the North; there is a quite good trend in Australia (especially for chip and particleboards); trends are likely to go up in Brazil, Russia, and China (especially for hardboard and fibreboard) (FAO, 2017).


Considering the data above, wood is an important global trade product. In 2007 the FAO stated that “over the last 20 years international trade of forest products [...] increased from US$60 billion to US$257 billion, an average annual growth of 6.6%”. However, some regions in the world, like South America and Central Africa (where the highest quality of structural wood can be found), have not developed the forestry industry, although they have extended forest areas. Europe and North America are the leaders in forestry market, in both the production of wood for economic activity and the consumption of wood and wood-related products like paper, as well as global exports and imports of wood (Hennig, 2015). Therefore, the equation “presence of forest = forestry commercial activity” does not apply.

Besides the simple presence of forests in a geographical area, another aspect to consider is how these forests are managed and regulated in relation to the private and public ownership. Europe, although relatively small (17% of the total land area), has 25% of the world’s forest resources; moreover, the amount of timber in the forest is increasing every year. However, the differences within Europe is very large: the largest part (81%) of these forest resources is within the Russian Federation. Europe is divided into three regions: Western Europe, Eastern Europe (including the Baltic States), and CIS countries (former Soviet republics). The forests in Western Europe are mostly privately owned (over 70%), while in Eastern Europe the share of privately owned forests is increasing from having been mainly state owned before the 90s. In most of the European countries, forest management is highly regulated by the government, meaning strict regulations on harvesting and re-planting (Swedish Wood, 2015). Therefore, the equation “presence of forest = forestry commercial activity” does not apply, when considering law and ownership.
The countries that produce the largest amounts of sawn timber are USA, Canada, Russia, Germany, and Sweden. Canada, Russia and Sweden are also large exporters of sawn timber. However, the sawn timber is often not addressed to the building industry (Swedish Wood, 2015). That is the case of Sweden, where the bulk of sawn timber is addressed to the furniture industry, whereas the wooden construction market is slow to develop: until now approximately 25,000 dwellings have been built using off-site timber construction techniques (Levander and Sardén, 2009). Therefore, the equation “presence of forestry = wooden buildings” does not apply, since there should be a link between the sawn timber industry and the construction industry.

On the other hand, the market of concrete is spread all over the world and is typically related to the world of construction; the technical and normative approach to this material has a long tradition and is well standardized. In emerging countries as China and India the concrete industry has an all-encompassing role in the construction market (China holds more than a half of the world’s cement consumption) and even South America, which has great wooden resources, keep using concrete (Portland Cement Association, 2013). Specifically for the building market, in the majority of cases, modern multi-story timber projects are set in Europe, Canada, United States and Australia, with timber being used either alone or with other materials like concrete and steel (Figure 4).

![Figure 4. Modern multi-story timber projects (source: http://www.whirlwindconsultants.com/).](image)

**Market perception and general approach for timber construction**

Viewing the data from the previous section, one could wonder about the reasons why timber construction market has difficulties expanding. The search for the weak points of this market can suggest where the concrete can help the timber. The main questions and the main perceptions/concerns (Table 1) regarding the timber building market may be summarized as (Green and Karsh, 2012):

- Are wood building solutions an alternative to steel and concrete buildings?
- What unknowns exist?
- What are the options to address the restrictions and open the door to wood buildings?
- Will wood buildings be feasible in the private development marketplace?
- What heights are technically feasible for tall timber buildings in real market conditions?
### Table 1. Common preconceptions to building with wood (Green and Karsh, 2012).

<table>
<thead>
<tr>
<th>Category</th>
<th>Preconceptions</th>
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<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>- Timber as material and as structure is more expensive</td>
</tr>
<tr>
<td></td>
<td>- Not enough competition in mass timber market</td>
</tr>
<tr>
<td></td>
<td>- Who will bear cost and risk?</td>
</tr>
<tr>
<td></td>
<td>- Details of timber structures add more cost compared to concrete structures</td>
</tr>
<tr>
<td></td>
<td>- Cost of fire protection</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>- Less freedom in design (prefabricated and shorter structural span)</td>
</tr>
<tr>
<td></td>
<td>- Thicker timber walls (reduction of floor area)</td>
</tr>
<tr>
<td><strong>Code</strong></td>
<td>- Fire resistance of wood cannot replicate the one of concrete</td>
</tr>
<tr>
<td></td>
<td>- Limitations in height</td>
</tr>
<tr>
<td></td>
<td>- Not adequate level of safety regarding the fire issue</td>
</tr>
<tr>
<td><strong>Structural</strong></td>
<td>- Timber is weaker than concrete</td>
</tr>
<tr>
<td></td>
<td>- Timber buildings cannot stand earthquake loading</td>
</tr>
<tr>
<td></td>
<td>- Envelope failure / leaky</td>
</tr>
<tr>
<td></td>
<td>- Deflects too much under wind and lateral actions</td>
</tr>
<tr>
<td><strong>Public opinion</strong></td>
<td>- Wood shrinks</td>
</tr>
<tr>
<td></td>
<td>- Wood rots</td>
</tr>
<tr>
<td></td>
<td>- Wood burns</td>
</tr>
<tr>
<td></td>
<td>- Glued wood emissions</td>
</tr>
<tr>
<td>**Economies</td>
<td>Evaluation</td>
</tr>
<tr>
<td></td>
<td>- Timber is exposed to moisture and to fire hazard</td>
</tr>
<tr>
<td></td>
<td>- Timber buildings are valued less than concrete buildings</td>
</tr>
<tr>
<td></td>
<td>- Insurance premiums are higher for wood buildings than for concrete buildings</td>
</tr>
<tr>
<td></td>
<td>- Timber cannot compete with the steel and concrete industries</td>
</tr>
<tr>
<td></td>
<td>- Not enough timber supply; sustainably managed forests</td>
</tr>
<tr>
<td></td>
<td>- Unexpected due to lack of knowledge and coordination in a not standardized market</td>
</tr>
</tbody>
</table>

In general, the majority of designers and population perceive timber buildings as being less durable than concrete, with the strong feeling that concrete is a preferable choice with better long-term value and performance. These perceptions are mostly due to many unexplored points about constructing with timber, such as:

- Lateral Load Resisting Systems (LLRS)
- Connection options
- Construction and erection engineering
- Cost analysis
- Fire testing and code

Proposing an initial project that does not “exceed the building code” might be a good mean to promote timber buildings. More designers would be enabled to develop timber buildings and the market would not be solely pushed from the timber manufacturers’ side. A project closer to design code, affordable and feasible since the very first moment, would lead to an overcome of the current concerns about building with timber (Green and Karsh, 2012).
3.2.2. Supply chain and stakeholders

Concrete supply chain

The entire concrete supply chain is mostly market oriented: productivity and competitiveness are the key factors of the concrete market; thus, project managers’ main concern is to deliver on time and on budget (Commonwealth of Australia, 2009). This happens because the concrete suppliers are more or less equivalent for the construction market, since concrete is often employed for ordinary buildings with simple design. Hence, the competition is intended as low price and easy availability, and the main issue is the procurement planning of the equipment; in fact, engineering, manufacturing and delivering the items are very uncertain operations, which may disrupt the construction schedule. The procurement process focuses on the evaluation of several suppliers according to the schedule and the budget targets, considering at the same time other constraints like the availability and the quality of the infrastructures (Azambuja and Brien, 2010).

Supplying concrete in an efficient and economical manner greatly depends on the distance between the batch plant and the construction site: while contractors are interested in delivery on time to ensure no interruptions in concrete placing, the suppliers are eager to reduce operational losses by minimizing trucks. Some boundaries in the concrete supply chain are represented by (Park et al., 2011):

- transport and logistics (both when delivering fresh concrete and precast elements);
- availability of supplementary materials to make concrete;
- building policies and standards agencies;
- environmental and social systems.

Despite concrete is a basic and standard material, the financial sector and building tenants, which provide leadership within the construction market, are facing new challenges, like the increasing demand to ensure sustainable investments. Moreover, practices and specifications for the use of concrete are highly contextual and are becoming stricter and more influencing. Typical new challenges are related to the design optimization, the improvement of time and logistics management to reduce waste, and the need of green buildings (Commonwealth of Australia, 2009).

In this perspective of optimization of the construction process and of the building itself, together with the sensibility about green construction, there is still confusion on what is sustainable in concrete. Some concerns relate to:

- limited specification of sustainable concrete by architects and engineers;
- project directors lacking incentives or knowledge;
- lack of sustainable concrete products and lack of awareness about what is sustainability.

Regarding the last point of the above list, a couple of examples could be mentioned: using supplementary cementitious materials (SCMs) - which are concrete waste products - without considering the context for their use, not necessarily leads to sustainable outcomes; or - again - attempts to reduce the use of concrete could adversely impact on the energy efficiency, durability, and longevity during the operational life of the building: the LCA should account the longevity of a building, and needs to inform of not just the decision of what to build, but how to build (Commonwealth of Australia, 2009).

Timber can help the concrete in its weak points:
• to improve decision-making support tools such as LCA;
• to give an additional option for the optimization of design, process, and product;
• to obtain incentives for sustainable building;
• to obtain contracts and procurement policies for green building criteria;
• to support decision making according to the green perspective.

Timber supply chain

The lack of experience and the absence of big companies pulling the standardization make the timber supply chain shapeless within the EPC industry. The problem starts within the forestry industry: how it is regulated in each country and how it is connected to the engineered wood product (EWP) manufacturers. Moreover, among the manufacturers, which are small or medium firms, there is a lack of standards on how to categorize the EWPs (e.g. production process, size, structural properties, etc.). Although there are some attempts to level out the EWP reality (e.g. minimum standards set-out by the recently published EN 16351:2015 to reduce the differences in the CLT panel performance properties), nowadays variations among manufacturers still exist and create problems for architects and engineers willing to design a timber building.

The lack of standardization leads to inefficiencies and challenges in the procurement process of a timber building. A EWP manufacturer must first be selected (usually through ‘design & build’ procurement) to commence the design of the structure: this means the engineer must either adopt a generic ‘loose fit’ design approach to produce a preliminary design or produce different structure designs for different EWP manufacturers. Moreover, the design and the supply of connections, must not be left apart either, as it is of paramount importance for a timber structure (Falk et al., 2016).

Then, it is only after the selection of the EWP manufacturer (and connection supplier) that the final design of the structure can be completed. This procedure is inefficient and puts pressure on the design process. For the time being, the only way to solve this problem is an early appointment of the EWP manufacturer and the connector supplier, speeding up the design phase and avoiding inefficiencies. However, by following this path, the design process of a CLT building would result fundamentally influenced by the choice of the EWP manufacturer and the connector supplier (Falk et al., 2016). On the contrary, the standardization of the timber market in the footsteps of concrete market, can lead to an open system and avoid problems when changing from one supplier to another in the middle of the process.

Therefore, as perceived from the section above, many boundaries influence the EWP supply chain:

• forestry policies and regulations;
• transport and logistics;
• availability of supplementary services, as connections suppliers and building service system;
• availability of human resources, as expert builders and designers;
• lack of standards in design and construction, and in operational building life as well (e.g. insurance and fire protection).

The lack of standardized design guidance represents the main challenge. Technical design data currently must be obtained from a combination of sources such as manufacturer’s European Technical Approvals (ETAs), experts’ reports and some design guides from timber authorities. This lack of consistency and formal agreement in how to design especially concerns new EWPs, like cross laminated timber (CLT), making the
designers go back to first and generic principles (e.g. Eurocode 5), not exploiting EWPs’ full benefits. (Falk et al., 2016).

As Keerthi Ranasinghe stated, “the standard committee should look at what we have currently as the state of the art and standardize that” (Falk et al., 2016). There should be fewer nationally determined parameters; this will enable greater freedom in the construction process and higher quality building. From the designers’ side, very simple rules should be provided for “lazy” architects and engineers; from the builders’ side, a better education of the workforce would help to close gaps between research and industry.

There are some improvements needed within the EWP supply chain that can find solutions by looking at the more standardized and expertized concrete practices. Some examples are:

- streamlining of the procurement and design process to avoid redesigning buildings because of a change in the manufacturers;
- affordable and easy-to-use structural analysis software for EWP structures;
- production of valid design guidance for EWPs and connection details;
- design guidance for timber structures in seismic locations.

A summary of concrete and timber supply chains with their interaction is presented in Figure 5.

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**Figure 5.** Concrete and timber EPC supply chain
Open and closed Market

The building systems, with respect to their connection with the industry sector, can be classified in two types (Swedish Wood, 2015).

- **Open systems**: specifications and building elements can be combined and purchased by anyone. Suppliers manufacture their elements based on an open standard of dimensions, which all suppliers adhere to.

- **Closed systems**: specifications and building elements are used by the supplier only, who makes his profit from the efficiency in building with the given system. Closed systems are suitable for integration of different functions in a company, for example design and production.

The earlier the decoupling point is placed in the supply chain, the more open the building system. Currently, there are no actual open building systems for EWPs. There is, however, an agreement on dimensions prescribed in EN 8560, according to which, actors in the timber building industry should design and produce elements in sizes of 900 mm, 1.200 mm or 2.400 mm (corresponding to 9 M, 12 M and 24 M). The open system also relates to the connections, which should allow flexibility and interchangeability in design (Swedish Wood, 2015).

Nowadays precast concrete elements are already well known and standardized (e.g. hollow slabs, double-T slabs, precast columns and beams); therefore, an engineer or architect can design rather independently, being secure that her specifications - if in accordance with the standards - would be fulfilled by a large bulk of concrete suppliers. On the contrary, the current differences between timber manufacturers create problems for the engineer designing a timber building, as its design is fundamentally influenced by the choice of the EWPs manufacturers and connector supplier. A set of standard drivers would enable greater freedom, bringing simplicity in the design and in the procurement.

A timber-concrete hybrid building would mean to enable the interchangeability between concrete and timber and to put timber in the same open system of the concrete industry. This could happen either adjusting the timber industry according to the concrete industry standards, or integrating both timber and concrete productions in a comprehensive industry.

### 3.2.3. Market indicators

When speaking about the EPC market, especially in such a timber-concrete hybrid case where innovation and market strategy counts besides the technical aspects, business criteria should be fully evaluated to undertake a wise and a complete decision-making path. Since dealing with business strategy, the classically proposed “market selection criteria” should be followed to build up a decision-making framework. (Papadopoulos and Denis, 1988).

For the timber-concrete hybrid case, the approach proposed by Ozturk et al. (2015) is here adopted, since it is flexible and practical to assist in market decisions based on industry-level analysis. The proposed criteria (Table 2) estimate the market potential based on country responsiveness, growth potentials and relevant macroeconomic variables in addition to industry-level approaches.
| Demographic environment | • Population age and gender segment  
|                         | • Income distribution  
|                         | • Market size  
|                         | • Infrastructure  
|                         | • Geographical/physical distance  
|                         | • Market similarity  
|                         | • Human resources  
| Political environment   | • Political climate/stability  
|                         | • Country risk  
|                         | • Corruption  
| Economic environment    | • Economic stability  
|                         | • Market growth/development  
|                         | • Economic/market intensity  
|                         | • Market consumption, middle class  
|                         | • Economic freedom  
|                         | • Long term market potential  
|                         | • Trade agreements  
|                         | • Trade barriers  
|                         | • Investment incentives, tax advantages:  
|                         | • Financial risk factors  
| Social-cultural environment | • Cultural distance, psychic distance  
|                         | • Language distance  
|                         | • Education level  
|                         | • Literacy rate  
| Sector/product-specific indicators | • Competitive landscape  
|                         | • Customer receptiveness, demand potential  
|                         | • Personal and social values of consumers  
| Firm-specific indicators | • Strategic orientation of the firm  
|                         | • Network relationships  
|                         | • Firm-related entry barriers  
|                         | • Motivations for growth and reputation  

**Demographic environment**

- **Population age and gender segment** and **Income distribution**: These factors might affect the demand of a timber-concrete hybrid building, depending on purchasing power, taste, and environmental awareness (see also **Market growth/development** and **Market consumption**).

- **Infrastructure**: Vehicles and traffic limitations set strict restrictions to the dimensions of carried products; consequently this affects the industrialization of the EWPs, which are prefabricated. The same issue applies to prefabricated concrete elements. Even when concrete is cast in-situ, fast and suitable tracks from the plant to the construction site are required and strongly influence the supply chain.
• **Geographical/physical distance**: The ecological and economic benefits of using wood products are related to the Life Cycle Assessment (LCA), which means that any transportation should be cut down. Plant and factory should be as close as possible to the raw materials for their industrialization, while construction site should be provided by close suppliers. This applies to both timber and concrete products. Therefore, the proximity of the interested area to forest and concrete plants should be evaluated, together with other influencing factors, as the ease of transportation of timber prefabricated products due to their low weight.

• **Human resources**: The presence of workforce (intended as both builders and designers) and their know-how is important in the construction industry, which is typically slow in changes and reluctant to innovation. Nowadays all designers and builders worldwide know how to handle the cast in-situ concrete. Lower experience exists for the precast concrete and even less for the EWPs. Precast concrete and EWPs have many similarities if thought as simple precast elements (e.g. same methods of lifting) but, at the same time, there are some particular issues, as design and assembly of connections, that are very different between concrete and timber structures. Both designers and builders need to be educated by providing simple standard rules and common practices.

**Economic environment**

• **Market growth/development**: In already developed countries and where the demand for housing has become static, one important driving force for using wood is to support a sustainable development of the society and aesthetics. In countries where the demand for housing is growing, wood, where available, could provide a fast and economical solution for buildings.

• **Market consumption, middle class**: It must be considered whether timber can be employed as a luxury material, to be allocated beside cheap concrete, or as an economic material to soften the price of only-concrete buildings. (see also **Market growth/development**).

• **Economic freedom**: It is important to check how much the government controls the construction market. A first concern regards the legislation on the sustainability of forestry industry. Then, more technical construction norms should be considered, which - for example - impose limits on the height of wooden buildings and on fire compartmentation. This has a certain importance, since there is not a well-defined international technical standard for wooden building, contrary to the concrete case. In particular cases, the possibility not to be in a liberal market context has to be evaluated as well, which would unable - for example - a potential partnership between concrete and timber industries. It is important to prepare carefully the project partnering construction contract, which should include, for example mutual cooperation and shared financial motivation, clearly defined roles and duties, and agreed allocation of risks (El-adaway, 2010).

• **Long term market potential**: (see **Market growth / development**)

• **Investment incentives, tax advantages**: Over time, carbon pricing will become an integral part of incentives, regulations and other market and legislative instruments (Commonwealth of Australia, 2009). As governments worldwide increasingly impose carbon taxes and levy fees based on environmental impacts of products, timber construction will enjoy a growing advantage as a renewable resource. Hybrid solution, whilst staying in the current building tradition, would benefit from the use of timber to alleviate the carbon taxes. In fact, it is expected that the cost of wood
would remain stable, whereas concrete and steel prices would continue to rise with rising energy prices and additional costs for carbon. If not carbon taxes, there could be tax benefits or incentives for timber buildings (Green and Karsh, 2012).

- **Financial risk factors**: The diffusion of timber buildings is also hindered by the high risk of such an “innovation” within the ECPs industry. In addition to all the difficulties coming from the lack of normative, experience, and stakeholders’ responsiveness, there is the issue of the insurance. In general, there are three types of insurances related to a new building type: “professional liability insurance”, “builder’s risk”, and “building property insurance”. These insurances (especially the builder’s risk) are more likely to have a high premium compared to concrete structures. The impact of insurance and risk valuation for timber building structures is difficult to measure: a timber-concrete hybrid solution will mitigate the “new building” factor and introduce in a soft way this timber building prototype to be evaluated. Nevertheless, uncertainties can turn out to be opportunities: as stated above, the future of carbon pricing suggests scenarios that are beneficial to timber solutions; in this perspective, mass timber is considered a lower risk material in the future, because it should be less vulnerable to energy price fluctuation and carbon emission penalties.

**Social-cultural environment**

- **Cultural distance, psychic distance**: Besides the cultural distance within the end users of the timber-concrete hybrid building (see Market growth/development), it is important to consider the differences in the cultural organization of the human resources working at the building (see also Human Resources), who bring with them a set of specific values related to the given construction environment. As a green field, a well-defined knowledge management for the timber-concrete hybrid construction does not exist yet; thus it should be fulfilled by taking into account the local differences of the work processes, yet maintaining a well-shaped scope (Di Marco and Taylor, 2010).

- **Education level**: This aspect is especially important if the timber-concrete hybrid solution is not meant as an exceptional stand-alone project, but as a common way to make buildings and a stabilized practice in EPC industry (see also Human Resources)

**Sector/product-specific indicators**

- **Competitive landscape**: Nowadays, the concrete market is oriented to sell ordinary products and just a few value-added products (VAPs). This means that the competition within the multinational concrete firms takes place in terms of price and easy availability in delivering, which works in an open construction system. Instead, the EWPs producers are small-medium firms that provide tailored products for each specific client, working according to a closed construction system. For the concrete companies being in a competitive landscape with several ordinary competitors, the adoption of timber could enable a virtuous differentiation. From the timber side, the juxtaposition with concrete can signify a step from the “exclusive building material” label toward the “affordable building material” label, enabling ample competition in the material marketplace and encouraging owners and designers to explore timber solutions for building. At the same time, the material marketplace will increase, over time, with demand. It is the proverbial chicken and egg scenario, that needs a sort of pushing force or initiative to be started (Green and Karsh, 2012). To conclude, as a broad-line, in concrete market the prices are set low because of the large competition and a timber-concrete
hybrid solution would push the timber market to take the same trend of concrete competition; but the “Competitive landscape” criterion has to be evaluated for the specific case: low price of concrete and high price of timber is not a rule, neither is it proportional to the gross domestic product or similar parameters (Portland Cement Association, 2013).

- **Customer receptiveness, demand potential:** The promoters of a timber-concrete hybrid solution could be several and act in different manners: the government willing to enable cheap and/or green housing solutions; privates that like wood but at the same time perceive the concrete as a more durable material; construction firms willing to give a fancy, yet cheap housing solution. (see also Market growth/development)

- **Personal and social values of consumers:** (see Market growth/development)

**Firm-specific indicators**

- **Strategic orientation of the firm:** This criterion regards the policy of the companies to start working within a very different building market. It requires a predisposition of the company to co-operate with each other, which practice is more common in countries like Sweden rather than countries like Italy, where the companies are very oriented to the competition. However, the collaboration among companies belonging to different market areas and segments could be convenient. From the large (concrete) firms’ perspective, such collaboration would be strategic for several reasons, like the desire to maximize their flexibility and effectiveness and the need for timber construction’s speciality; form the small-medium (timber) firms’ perspective, the motive for a collaboration could be to access a large construction market, overcoming the lack of ability for risk management and the difficulty of receiving independent orders from contractors (Son et al., 2010). Therefore, the concrete-timber firms’ collaboration could be more incentivized than the concrete-concrete and timber-timber collaborations. (see also Competitive landscape)

- **Network relationships.** This aspect is of paramount importance, considering the extremely complex nature of the construction and supply chain process; communication, coordination, and cooperation among stakeholders are important drivers to create a successful project environment, always keeping in mind the singularity of the relationship among the various stakeholders in planning, design, construction, and operations (Son et al., 2010). In a vertical way, the network involves decision makers, suppliers, manufacturers, and legal and political entities; from the concrete side, a problem - for example - is that builders are reluctant to use the concrete VAPs proposed by the suppliers; from the timber side, there is a problem to reach a smooth collaboration between the forestry industry and the EWP manufacturers. In a horizontal way, the relationship between timber and concrete producers should be considered: timber producers could find impulse riding the wave of the concrete market, whereas concrete producers could improve their image and explore a new market, also reaping political benefits. Although firms often tend to maximize relations within a cohesive group in order to reduce uncertainty, maintaining trust-based long-term relationships with strong partners, it is essential for them to extend their network as well, in order to enter new business opportunities through sharing information and know-how, and gain market share (Migliaccio and Martinez, 2010).
• **Motivations for growth and reputation** (see *Strategic orientation of the firm* and *Network relationships*)

3.3. Conceptual design

In the previous section the focus was on the economic factors to be considered when evaluating the employment of timber and concrete in a hybrid construction. In the following sections, more technical and practical factors are considered, with the purpose to exploit the materials potentialities and obtain their best matching, in a holistic perspective. This is done following the lean principles that aim at the optimization of the process through collaboration and systematic learning, continuous improvement, and elimination of the obstacles to value creation and inefficiencies, with the main intent to obtain perfection in delivering the final result (Enache-Pommer *et al.*, 2010).

Careful planning and good coordination among the architect, the engineer, the suppliers, and the contractor are especially necessary when dealing with prefabricated elements like precast concrete and EWPs, where the early consultation with the supplier is necessary for the good outcome of the project. Even more attention must be paid when two materials with different properties and industrialization processes must reach compatibility. Therefore, a systematic approach and a high degree of standardisation should be adopted in the architectural design, in order to achieve maximum economy and optimum quality.

3.3.1. Flexibility, modularity, and standardisation

Nowadays, flexibility in architectural design is of paramount importance. An open plan (achievable by not using inner load bearing walls) allows a great variety of uses of the building (e.g. residential, office, hotel, etc.), which may change with time. Flexibility in high rise buildings is even more important, since the same building could be used for different purposes at each storey. It is also important to have the opportunity to adjust the exterior envelope of the building and adapt it to a number of specifics related to the context: architectural shape, lighting and thermal performance, acoustic insulation, and maintenance. The flexibility and interchangeability especially apply when a specific building is designed starting from a base model: from here comes the equation “flexibility = modularity = standardization = open system”.

Flexibility also applies to the opportunity to use various materials and products fulfilling the same requirements. Then, one could choose among various EWPs or perhaps have the possibility to substitute them with concrete equivalents, if the requirements of the building change. Different EWPs each have their own unique properties, but for the purposes of this building system they are essentially interchangeable in most of the cases (Green and Karsh, 2012). Taking into account these conceptual design drivers and architectural considerations, the prefabrication of building components represents the most suitable solution for construction optimization.

Nevertheless, construction developments have not gone into prefabricated technology in general; most of the buildings, especially if residential, are unique in nature and lack repetition (Singapore Institute of Architects, 1999). This is a problem which the precast concrete and the timber building have in common; from the concrete side, the issue is that the possibility to cast on site hinders the procedure of building by employing prefabricated standard products; from the timber side, the construction products are all tailored in the factory, but without any standardisation. The solution would be to offer a clear set of standard products and sizes that enable a combined employment of both materials and their compatibility and interchangeability.
Regarding concrete, the common perception is that precast concrete lacks flexibility. However, by using more industry standardised components (e.g. staircases, internal and exterior wall panels, etc.), the cost for precast components would be reduced. For example, the traditional method of applying exterior finishes on site can be avoided by using pre-finished concrete components (Singapore Institute of Architects, 1999). On the other hand, timber-only constructions present limitations in flexibility as well; the required loadbearing structure becomes disadvantageous to the design flexibility, especially as the building becomes taller. In some cases, a structural core is enough to assure the stability of the building, allowing a certain flexibility of the floor plan. For increasing height, interior load bearing walls might be added, with a decrease of the flexibility in the floor layout and its eventual changes. In even higher building, also exterior structural walls are needed, preventing flexibility in the design of the façade (Green and Karsh, 2012).

Buildings made of standard timber and precast concrete components can be designed economically with a variety of plans and height, with the awareness that design should not be a mere conversion from projects of cast in-situ building. Instead, the approach to the design should be more oriented to the concepts of modularity and off-site production, according to the lean principles and a higher level of industrialization.

Modular planning

Modularity is the key to succeed when designing with the purpose to obtain flexibility (and then standardization and open system). When dealing with prefabricated components - especially if made of different materials, like concrete and wood in a hybrid construction solution - modularity allows to obtain the coordination necessary for the combination and the interaction between them.

The modular coordination starts in the architectural design stage. The basis for modular planning is to set out a suitable layout design with uniform pattern (Building and Construction Authority, 2010); the modular distance between the grid lines shall, as far as possible, be equal (Figure 6). The basic modular grid will define the major planning line-up where the main structural components (e.g. columns, beams, and floor slabs) are placed and co-ordinated, avoiding strictly defined arrangements. Thereafter, the architect must decide where to place the architectural components: for example, the wall panels may be placed on the outer part of the grid or in-line with the grid. The overall design layouts results from an assembly of many similar sub-modules or clusters, which could be repeated, turned, or mirrored (Singapore Institute of Architects, 1999).

The most common modular reference system of a basic planning grid is set to 300 mm (or 3M, where M = 100 mm). In general, 3M is recommended for the horizontal multi-module and 0,5M for the vertical multi-module. Table 3 presents the recommended modular dimensions that will provide sufficient flexibility in the design of the buildings; this means that the elements of the building can have dimensions that are multiples of the listed modular units. It is also possible to introduce sub-modular increments of 0,25M or 0,5M.
Even considering only the precast concrete industry, several benefits of modular coordination can been identified (Singapore Institute of Architects, 1999):

- better co-ordination in the design and construction stage and therefore reduction in design time, speed of production, and manufacturing of components;
- improvement of structural and architectural quality of the building;
- reduction of wastage of labour and materials;
- increase of the speed of erection of standardised components and joint details.

A certain tradition of modular coordination within the precast concrete industry already sets out some established prefabricated elements (see Annex A), which could be considered as starting point towards standardization and compatibility among timber and concrete elements and hybrid construction. Concerning timber, the EWP are all made in factory and the modular co-ordination should be necessary. Nevertheless, the lack of regulations and standards has led the timber industry to choose different sizes; each producer had freely developed its own solution with its own format. An effort to uniform sizes, by following the already existing main products, the modular coordination guidelines, and the match with the concrete market is presented in Annex A.

### 3.3.2. Materials’ properties and construction products

As said, there could be many economic and technical reasons to select a hybrid building solution; however, the main intent is to exploit the materials and their industrialization, considering both technical and convenience aspects. Hence, it is important to be aware of the properties of both concrete and timber, since one can compensate for the weak points of the other and increase the possibility to optimize the employment of the resources within the building. Annex B provides an overview of timber and concrete’ properties and construction products, highlighting some aspects useful for designing.
3.4. Production information and construction

When introducing a new solution into the EPC market, there are many economic factors to be considered for a decision-making process; but these shall be put into relation to the technical solutions, which in the EPA industries are barely standardized. Therefore, it is necessary to consider the technical aspects as interconnected among themselves and related to the economic ones. The main technical issues identified from both timber and concrete constructions are: structural design, fire protection, building technology details, and constructability.

3.4.1. Structural design

Lateral loading resistance system

For concrete, a certain experience about the seismic behaviour has been developed after numerous events of earthquake; therefore, national and international codes set specific design rules and practices on seismic design. On the contrary, the seismic experience in timber structures is modest and often in absence of guidelines. Specific tests on samples are carried out time after time to understand how the timber structures behave, which is time spending and expensive. Nevertheless, even if not yet fully exploited, the great ductility in a timber frame ensures good racking resistance under earthquake loading.

For lateral action as earthquake or wind, an adequate bracing system is needed to provide both strength and stiffness. If brace connections are too flexible, they can be very bad for the stiffness of the main structure. The main scopes of the bracing system are (Swedish Wood, 2015):

- providing lateral stability to members working in compression or bending in order to prevent lateral or torsional displacements due to horizontally-acting wind or earthquake loadings. In addition to translation (direct shear), rotation (torsion) is also generated, the magnitude of which is influenced by the building proportions;
- increasing the buckling strength of the primary members such as beams and columns, by employing the same bracing element used to prevent lateral movement due to external transversal loading (wind and earthquake);
- assuring good comfort in the upper storeys of tall building against possible horizontal deformation: here it is likely to use a core that connect the building along its full height from foundation to roof.

In ordinary buildings, lateral stiffness is provided through truss or diaphragm action within the plane of the bracing structure, as the following options (see Figure 7):

- Diagonal member to the structure
- Rigid planar surface elements stopping the angular changes that occur between structural members
- Rigid connections or joints

Normally, concrete slabs and some types of decks are considered to be rigid diaphragms, which are assumed to distribute the horizontal forces to the supporting vertical structures in proportion to their relative rigidity \( R \). It is important to observe that if the bracing is not adequately stiff, the maximum load carrying capacity of columns and beams cannot be achieved (Swedish Wood, 2015).
Shear forces are transferred from the roof walls and floor diaphragms onto the foundations via a system of connections (Figure 8); for the Lateral Load Resistant System (LLRS), the following alternatives are possible:

- diaphragm action of the roof, which transfers the horizontal load to wall diaphragms, normally placed in the gable walls;
- wind trusses in the roof, which transfer the horizontal load from columns to braced columns, normally placed in the gable walls;
- structures rigidly connected to a wall diaphragm in its own plane.

Oftentimes, bracing is also needed during the construction stage, perhaps by means of temporary devices. Thus, it should be studied how lateral actions undermine the temporary structure in intermediate stages of construction (Swedish Wood, 2015).

Tall buildings

In tall buildings, it is necessary to assure stability and good comfort also in higher storeys against possible horizontal deformation. Often a core is built to connect the building along its full height, from foundation to roof. Generally, diaphragms are largely employed: either concrete or solid wood panels, connected together, are able to transfer the required shear forces, according to the following solutions (Green and Karsh, 2012):

- **Core walls and headers**: The core must be an entire unit running from the foundation to the roof. It could be made of cast-in situ concrete as a monolithic piece, or made of LSL, LVL or CLT panels installed vertically and connected together to create larger wall panels; usually ductile beam headers partially embedded into the panels are used to connect the core wall panels together over doors and other openings.
• **Perimeter wall moment frames**: Panels installed vertically and connected together, often linked by “weak” ductile steel headers, create a ductile “strong column / weak beam” moment frame. In general, for the push over analysis, a large number of plastic hinges on the beams are tried to get before failure, so that a large amount of energy can be absorbed.

• **Interior partitions / load-bearing walls**: Interior walls are made to be continuous and load-bearing from foundation to roof. More likely they could be used as a complement for the primary LLRS, to achieve adequate stiffness under wind loading rather than under high seismic actions. This strategy would allow the partitions to remain non-loadbearing, but would require the interior walls connected to the floor diaphragms to remain sufficiently ductile to provide stiffness under wind loading while accommodating the drift of the primary LLRS under ultimate seismic loading conditions.

The main difference between cast in situ concrete and precast concrete or timber panels is that the panels must be properly connected to each other to create larger wall panels working as one piece. Whatever LLRS solution is chosen, walls must be a monolithic piece running from the foundations to the roof.

**Lateral loading resistance system in timber structures**

As skin-framed structures, timber structures are normally rather flexible: beams and floors are designed as simply supported elements and the lateral strength and stability of the structure is provided by vertical diaphragms or shear walls together with floor decking, which have relatively high in-plane stiffness. However, mass timber panels provide an effective lateral load resisting system only if good design of connections is ensured, according to the following recommendations (FPInnovations, 2011):

- Good performance is achieved when nails or slender screws are used with steel brackets to connect the walls to the floor below (but not in case of high seismic zone, because this solution leads to low ductility and thus brittle failure)
- Use of step joints in longer walls reduces the stiffness and improves deformation capabilities.
- Platform structural systems (as in CLT building) are less susceptible to develop soft storey mechanism; the non-linear behaviour is localized in the hold-down and bracket connections areas, while vertical load carrying panels are left intact in place and well connected to the floor. Also, all the walls contribute to the lateral and gravity system
- Studs must be well connected to foundations

Shearing panels may be made of wood-based materials as plywood, OSB, hardboard; although gypsum boards and various types of cement-based boards can also be used as shearing panels. Nevertheless, it is important to fix the sheathing to the framing; this is normally made by means of nails or screws. The shear stiffness of the walls mainly depends on the stiffness of the sheathing-to-framing joints; it is crucial to properly fasten the shearing panel to the frame with shear connectors to the purlins and to the perimeter members so that shear can be transferred (Swedish Wood, 2015).

Since the seismic design of timber structures relies on a good design of the connections, great attention should be payed to damping problems. In damping of floors consisting of joists and sheet materials, roughly half of the energy dissipation is due to material damping, while the other half is caused by structural damping, i.e. caused mainly by energy dissipation in connections and interaction between mating surfaces. For example, the damping of dowel connections is due to the friction between mating surfaces of the dowels and the surrounding wooden material; in some cases, it leads to high concentration of stresses around the dowels with consequent crushing, cracking, or compression of the wood (Malo, Abrahamsen and Bjertnaes, 2016).
Nowadays, European design procedures only deal with the ductile design modes to determine the lateral load resistance by means of empirical expressions of European yield model (EYM), treated in Eurocode 5. Brittle failure mode has not been investigated yet. The practice today for seismic design in mass timber building, is to calculate the $R$ values; all the commonly used lateral load resisting systems are assigned $R$ values in the national building code. The higher the ductility of a system, the higher the associated $R$ factors and, as a result, the lower the required seismic design forces. $R$ values have yet to be assigned for solid wood panel construction in the building codes, leading engineers to use practical tests to determine the seismic behaviour (FPInnovations, 2011).

**Lateral loading resistance system in concrete structures**

In general, cast in-situ concrete does not require bracing, since connections (e.g. between columns and beams) are monolithic and therefore rigid, and can provide good in-plane stiffness of the frame. Things are different for precast concrete elements: great attention should be payed to the connections between the key elements (columns, beams, and floors). In fact, the combination of vertical and horizontal earthquake waves could pull the elements out of their supports. This concerns both the beams propped against the columns and the floor elements propped against the beams. The dry supports with only rubber pads between beams and columns are sufficient for static actions but must be excluded in a seismic area, where mechanical connections are needed to transmit forces (Bonfanti et al., 2008).

In structural frames made of precast slabs, columns and beams, it is necessary to maintain continuity of reinforcement by overlapping the reinforcement or by providing ties joining the precast elements and to provide a fair degree of continuity between the non-structural precast elements and the structural frame (PCI Industry Handbook Committee, 2004). The correct positioning and dimensioning of joints is of paramount importance in a prefabricated structure made without shooting irons neither additional castings. Considering that the connections of prefabricated structures are generally not ductile, they must be positioned outside of the dissipative critical areas of the structure. Moreover, transverse constraints of the beams to their supports on the pillars are required to prevent the lateral overturning. In general, connections are designed with such restraints to prevent excessive deformation of the structure.

However, lateral bracing is often needed, and is indispensable in tall buildings. There are several combinations of stabilizing systems (Table 4); braced frames, elevator shafts, stair or service cores are effective structural systems providing lateral stability and the additional cost of utilizing them as stabilizing system is negligible. These systems are capable to carry in-plane horizontal loads in a manner like that of a deep beam and transfer lateral load to the foundation. Floor diaphragms with sufficient stiffness are necessary to ensure coherent response of the structure to seismic action, spreading it evenly on the different resistant elements and avoiding uneven vibrations among the different parts of the structure; a bumpy response leads to significant distortions of nodes and non-structural elements (Bonfanti, Carabellese and Toniolo, 2008). Adequate propping and bracing must be provided at all stages of construction, by means of temporary devices, until the joints gain sufficient strength for flexural and shear continuity or until other definitive stabilizing devices are installed (PCI Industry Handbook Committee, 2004).
Table 4. Typical combination of stabilizing system (PCI Industry Handbook Committee, 2004)

<table>
<thead>
<tr>
<th>Stabilizing component</th>
<th>Frames</th>
<th>Load bearing walls</th>
<th>Load bearing facade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilever column</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame with moment resisting connections</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor diaphragm</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Shear wall</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Central core</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

**Vibration**

Given the light weight of timber structures, the wind-induced vibration must be considered in the structural analysis. Buildings subjected to fluctuating wind might start to vibrate and lead to discomfort of the occupants. The fundamental frequencies and corresponding vibrational modes of a building depend on the stiffness and the masses as well as on how they are distributed.

The solutions could be many. It is possible to work on the mass: for example, in “Treet” building in Norway, a concrete topping has been laid on some floors and on the roof essentially to add mass to the structure and lower the vibration. It is also possible to work on the stiffness, by using permanent mass timber partitions to mitigate vibrations. This solution is commonly used in residential buildings but usually absent in commercial construction, where open space is required. Also, in order to achieve a low vibration, it is better to have a stiff basement made of concrete (Malo et al., 2016).

Another aspect to consider is the study of connections. Besides the choice of the type of connections, it is important to check whether it is better to connect timber elements among them and together with the concrete ones, or leave them simply fixed one upon another. Nowadays, there is not an established design calculation to check this aspect and often practical tests are carried out on mock-ups, as for the design of “Treet” building in Norway (Malo et al., 2016).

**3.4.2. Fire protection**

A common concern when considering timber buildings is the fire protection, which implies many limitations for wooden buildings, mostly due to uncertainty and lack of knowledge or experience; this has implications for the insurance fees as well. Fire regulations are different depending on each country or region’s code. Notwithstanding the lack of well-defined regulations and international standards, common practices on how to deal with fire protection can be found in handbooks.

Fire compartments and escape roots are one of the major limitations for freely building high structures with timber. Some countries have very strict limitations; for example, Russia establishes the maximum height of the building at 3 storeys with a compartmentation of maximum 1500 m² (Pavlyukovskiy, 2012). Other countries like Canada, where engineers are more expert and prone to build with timber, agree upon less restrictive rules for the fire protection in tall building. The code recognizes that the level of risk increases with the height and area of the building; then it determines the maximum area to be built in relation to the height and number of floors (Veilleux et al., 2015). Buildings of more than 6 storeys must be non-combustible construction, which means that load-bearing elements and floors must have a fire-resistance rating of at least 2 hours. Imposing a building height limit with respect to ground level is intended as a limit for the number of timber floors, which represent fire load. The height and building area limits for buildings over 6
floors can be found in Table 5. However, the Canadian guidelines limit the height of a massive wooden construction or hybrid construction to 12 storeys (13 if the building is erected on a stage concrete podium) and to a maximum of 40 m. The maximum area of a building made of timber depends on its class of use; in most cases the set building area is 15,000 m².

Table 5. maximum area of buildings in relation to the height (number of floors) (Veilleux, Gagnon and Dagenais, 2015)

<table>
<thead>
<tr>
<th>Height (storeys)</th>
<th>Construction Type</th>
<th>Degree of fire resistance</th>
<th>Sprinkler</th>
<th>Building area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited</td>
<td>Incombustible</td>
<td>2 h</td>
<td>Yes</td>
<td>Unlimited</td>
</tr>
<tr>
<td>7 à 12</td>
<td>Mass timber</td>
<td>2 h</td>
<td>Yes</td>
<td>1500 m²</td>
</tr>
<tr>
<td>6</td>
<td>Incombustible</td>
<td>1 h</td>
<td>Yes</td>
<td>6000 m²</td>
</tr>
<tr>
<td>6</td>
<td>Combustible</td>
<td>1 h</td>
<td>Yes</td>
<td>1500 m²</td>
</tr>
<tr>
<td>4</td>
<td>Combustible</td>
<td>1 h</td>
<td>Yes</td>
<td>1800 m²</td>
</tr>
<tr>
<td>3</td>
<td>Combustible</td>
<td>45 mins</td>
<td>Yes</td>
<td>1800 m²</td>
</tr>
<tr>
<td>3</td>
<td>Combustible</td>
<td>45 mins</td>
<td>No</td>
<td>900 m²</td>
</tr>
</tbody>
</table>

Generally, in Europe, the Austrian Institute of Construction Engineering (OIB) guidelines can be taken as reference point (Figure 9) (Teibinger and Matzinger, 2013):

- For general components, 60 minutes fire resistance is required
- For components that form fire compartments, 90 minutes fire resistance is required
- For components of the top story, 30 minutes fire resistance is required
- Maximum fire compartments in above-ground storeys is set to 1,200 m² if residential and 1,600 m² if offices, with a maximum length of 60 m.
- Fire compartments must not span more than 4 storeys above ground (max escape level at 11 m)
- Façades and elements between apartments or operational units must resist for 60 minutes, whereas components forming fire compartments must resist 90 minutes

Figure 9. Fire compartmentation of a timber building according to ÖNORM EN 13501-2 (Teibinger and Matzinger, 2013)
The compartmentation is obtained by using elements that are fire-resistant, which means that they should fulfil certain requirements with a certain class performance (see Table 6). These requirements are: load bearing capacity (R), Integrity (E) and heat insulation (I).

Table 6. Designations for fire resistance according to ÖNORM EN 13501-2 (Teibinger and Matzinger, 2013)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Requirement</th>
<th>Component example</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 30, R 60, R 90</td>
<td>Load-bearing component</td>
<td>Support, wall, beam</td>
</tr>
<tr>
<td>EI 30, EI 60, EI 90</td>
<td>Space-enclosing, heat insulating component</td>
<td>Non-load bearing separating components, shaft walls, partitions</td>
</tr>
<tr>
<td>REI 30, REI 60, REI 90</td>
<td>Load-bearing and space-enclosing heat-insulating component</td>
<td>Load-bearing component</td>
</tr>
</tbody>
</table>

For a mass timber building, there are two primary design methods to achieve acceptable structural passive fire protection (and thus fulfil the load-bearing requirement R) (Teibinger and Matzinger, 2013):

- **Charring Method**: Due to the ability of wood to form a protective char layer during combustion, the size of structural elements can be calculated starting from a minimum structural thickness and adding the remaining sacrificial thickness available for charring. A simplified method allows to calculate the reduced cross sections by employing the reduction factor $k_0$ for the determination of the ideal burn-up depth $k_0d_0$ starting from the overall thickness $d_0$. This method has taken root in Austria and is currently under international discussion, especially for the value of $k_0$ stated in the current standard (e.g. for CLT, 0.65mm/min is the generally accepted average of the charring rate, but it is not a standard yet)

- **Encapsulation Method**: fire protection is attained by applying two layers of fire-rated gypsum boards (or other fire-resistant boards) to the sides of the panels and in general throughout the building.

The charring method is increasingly accepted around the world as a valid mean for achieving reliable and safe structural performance in fire; its reliance is due to both laboratory tests and previous successful applications in the past. Combined with modern fire suppression systems and compartmentalization, timber structures can ensure fire resistance by using charring calculation methods. This eliminates the need for encapsulation, reducing building weight and cost while showing the natural beauty of the exposed timber. Moreover, to fulfil the fire protection requirements, often no changes to solid wood panels are needed, as other factors (e.g. acoustic, lateral loading) determine the minimum size required for these elements (Green and Karsh, 2012). On the other side, concrete has always been considered a fire-resistant material, especially when designed with gypsum protection layers; furthermore, there are some precast products, like Glass Fiber Reinforced Concrete (GFRC) that could help to obtain a high fire resistance without adding any further protection.

As an integrated system that shall fulfil several requirements, additional recommendations need to be specified on walls forming fire compartment (Figure 10) (Teibinger and Matzinger, 2013):

- On the edges, non-combustible claddings and coverings are to be used
- Joints, connections and installations must be carried out in an airtight way
- Electric installations need to be laid in shells
- If shafts, conduits, pipes, and other devices run in walls or floors or penetrate them, appropriate measures (e.g. partitions, sheathing) must ensure that the fire resistance class of these components is not deteriorated and that propagation of fire and smoke are effectively restricted over the required fire resistance period
3.4.3. Design of building technology details

Building technology and details, as stratigraphy of floors, partitions, external walls and their connections, are influenced by various factors besides the simply load-bearing capability. Some of these factors have been listed above, like fire compartmentation, and vibration, but an important aspect to consider is the energy performance of the building. Here the climate context is of paramount importance: the thermal loads are strictly connected to the climate conditions (e.g. external environment temperature, external relative humidity, exposure to the sun), which go beyond the simple properties of the material like thermal conductivity and thermal inertia. The Indoor Environment Quality (IEQ) also affects the design of the building, taking into account other factors like the release of compounds and the ease of cleaning of the building surfaces; moreover, it is strongly affected by the subjectivity related to the psycho-physic conditions of the occupants.

Building elements are made of several components that should satisfy certain requirements and serve specific scopes (see Table 7). Building technologies and details in concrete building can rely on strong know-how and a broad set of normal practices. Most of the timber technologies have been built up basing on the equivalent existing concrete solutions, but some particular elements should be highlighted. Therefore, the focus here is on timber components, where the main factors influencing the detail design are fire protection, thermal performance, acoustics, vibration and weather protection. (In the following examples, the CLT is often represented as the main EWP, but the same technology solutions apply to the other EWPs).

Table 7. Component layers and relative requirements in typical building elements (Teibinger and Matzinger, 2013)

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior cladding</td>
<td>Fire protection, sound protection, heat protection in summer</td>
</tr>
<tr>
<td>Insulated facing shell</td>
<td>Sound protection, fire protection, air tightness of facing shell (retrofitting of electrical installations possible)</td>
</tr>
<tr>
<td>Cross-laminated timber element</td>
<td>Bearing behaviour, fire protection, air tightness of facing shell</td>
</tr>
<tr>
<td>Heat insulation</td>
<td>Heat protection, fire protection (e.g. for floor-overlapping external wall strips), sound protection</td>
</tr>
<tr>
<td>Façade</td>
<td>Weather protection, fire protection, (fire propagation)</td>
</tr>
</tbody>
</table>
External wall

External walls (Figure 11) should be carefully designed and realised, since they constitute the envelop of the building and thus have a fundamental role in its energy performance and comfort. Here listed some peculiarities.

- Some EWPs like CLT generally work as a moisture buffer; thus, a vapour barrier may not be required, depending on the specificity of the climate areas.
- EWPs often assure air tightness, but a flow-tight sheet can be added to achieve an extremely low energy consumption building or passive house.
- Sound insulation is to be considered: a decoupled and insulated shell can solve the problem.
- EWPs provide quite good thermal insulation by themselves, but depending on the external environment, insulation materials could be added (this is the case of Sweden). Attention should be payed to the thermal bridges; the impact of element joints can be neglected by mounting insulation layers within façade claddings and dry linings or direct internal claddings, as normal practice for the concrete case; in this way, wide distributions between individual solid timber elements can be greatly reduced.
- Storage-effective mass is a weak point of timber compared to concrete, which is capable to improve the thermal inertia performance of the building. Use of decorative wood or direct claddings can increase storage-effective mass in timber constructions.

![Figure 11. Example of external wall based on mass timber (source: www.dataholz.com)](image)

Partition wall

In its simplest form, partition walls (and load-bearing internal walls) can be made up by a simple EWP panel; however, sound insulation is another important requirement for design, thus gypsum boards on one or both sides of the wall are usually added.

- Partition walls can be built with one or two leaves (Figure 12)
- For a single-leaf partition wall, completely decoupled shells on both sides are required at any rate.
- In a double-leaf partition wall, the greater the space between the leaves (≥ 5 cm), the higher is the sound reduction index; at any rate, this space needs to be completely filled up with stone wool for sound insulation, since a continuous air layer is inadmissible for reasons of fire and sound protection.
- If the floor is constructed as a continuous floor, then a suspension is required.
- Joints, connections and installations shall ensure airtightness.
• For sound insulation reasons, it is recommended not to install water pipes or sanitary and heating pipes through the wall.

Many options are possible for the stratigraphy of the inner partition:

• single-sided cladding
• double-sided cladding
• single-sided insulated facing shell
• double-sided insulated facing shell
• single-sided facing shell, completely decoupled with cavity attenuation
• double-sided shell, completely decoupled with cavity attenuation

![Figure 12. Example of a) single-leaf and b) double-leaf partition wall based on mass timber (source: www.dataholz.com)](image)

Floor elements

In timber buildings, the structure is rather independent from the floor system since various EWP{s} can be chosen to be loaded on the vertical load-bearing system, unlike its concrete counterpart where floors are cast to be monolithic with the walls and columns or, when dealing with prefabricated elements, connections between slabs-beams and beams-columns should be considered earlier in the design stage. This affords great flexibility in terms of options for timber floor assemblies (Green and Karsh, 2012).

From a structural point of view, the challenge for a good design is to limit the total depth of the floor for given span lengths. In timber floors, this is governed by serviceability requirements concerning vibrations and deflection. Moreover, the design strongly depends on the requirements concerning fire resistance, sound performance and integration with services. Floor elements made of solid wood can be divided into three main types (Figure 13 and Figure 14). The choice among these types basically depends on the span and the level of sound insulation required (Swedish Wood, 2015).

• **Plane elements**: nailed or dowelled plates, stress-laminated plates, cross-laminated plates. Plane floor elements must usually be accompanied by either a floating floor or a suspended ceiling, due to the sound insulation requirements.

• **Cassettes**: plates with empty spaces, for example H-beams (made of thinner beams of structural timber, LVL or glulam as webs and solid wood or wood based panels as flanges).
• **Composite floors**: made of timber and concrete (different designs are possible). Good technical performance is achieved, but are quite expensive to produce. The idea is to have timber in tension and concrete in compression, whereas the fasteners are loaded mainly in shear. The stiffness of the connections completely governs the performance of the floor. Composite timber-concrete structures can also be used to restore existing timber floors by casting a concrete plate on top of already existing joists. Floor spans can reach up to 12 m (pre-stressing techniques are employed to reach even longer spans).

![Figure 13. a) CLT floor, b) cassette element c) composite floor design (Swedish Wood, 2015)](image)

A typical issue of the timber floor is the transmission of the sound. This can be solved by decoupling floor and ceiling, which is the best solution, or by adding a subfloor for approximately the same total floor thickness. However, the Sound Transmission Class (STC) and the Impact-sound Insulation Class (IIC) ratings are much lower for floors built with a subfloor compared to floors built with a suspended ceiling.

The suspended ceiling cannot be connected to the floor; thus, it needs a separate load-bearing structure and the void space shall be filled up with insulating materials, which usually is made of a double gypsum board or fibreboard suspended in metal sheet profiles. Separation between top and bottom parts of the floor is an advantage automatically obtained in prefabricated volumetric type construction (Swedish Wood, 2015).
Another way to provide a good and economic improvement in impact sound level reduction in multi-storey timber constructions (keeping approximately the same total floor thickness), is to use floor surfacing cement or sound insulation slabs, usually carpets. Moreover, any floor surfacing that is applied to floors in a permanent way, such as screeds, glued-on parquet and ceramic tiling, is to be accounted for their sound reduction properties. It is possible to combine sound-insulated floor assemblies on both sides, i.e. the floating floor on the top (Figure 15 a and 15 b) and the ceiling on the bottom (Figure 15 c) at the same time; there would be no significant improvement for STC, but IIC ratings significantly increases (FPInnovations, 2011).

![Floor assemblies for sound-insulation: a) floating floor on lumber sleepers; b) floating floor glued; c) detached ceiling (FPInnovations, 2011)](image)

There are other details to consider in a timber floor:

- Timber floors are frequently used for a wood bottom view; thus, there is the need for an improved floor construction to preserve the aesthetic aspect.
- Sound bridges towards the screed near walls, supports and installations should be avoided through edge insulation strips (Figure 16).
• In case of floating floor, coupling between screed and raw floor should be prevented by means of a continuous separating film, especially where there are intersections of pipes. At any rate, attention needs to be paid to airtightness around electric installations.

3.4.4. Building service systems

The building service systems are subordinated to the structural system in its design (Lennartsson, 2009). The standardization and modular planning entailing the compatibility and interchangeability between concrete and timber elements, should be carried out considering the allocation of the service systems since the early stage of design, in order to enable a smooth integration of the building services (electricity and HVAC) within the industrialised timber-concrete housing.

Services installed in the apartments, like water, electricity and low current, are generally of small size (Figure 17). These are usually placed in the shafts close to or inside the staircase, which makes them accessible for service work. Only the ventilation ducts are space-demanding and require a more detailed design.

Generally, in multi-storey building systems, it is favourable to lead the services vertically to reduce the number of passages between fire cells (Figure 18). It is advantageous to have multiple vertical shafts (one shaft for each staircase) so that a large number of horizontal pipes can be avoided (Swedish Wood, 2015). Currently, due to the easiness of making openings on site, the general practice in industrialised timber housing is not to prefabricate the shafts, meaning that all vertical canalisations and shaft assemblies are
made on site (Lennartsson, 2009). This is a good point to further modify the building system, which is easier compared to concrete elements; nevertheless, as a principle, the shafts shall be thought at the beginning of the design and allocated in strategic modular positions allowing flexibility in case of future modifications.

Figure 18. a) Single and b) multiple shafts for services (Lennartsson, 2008).

There is need of fire insulation for the shafts, both vertically and horizontally (Figure 19). This is achievable in two ways, varying the location of partitioning measures of penetrations (Green and Karsh, 2012):

- **Shaft type A**: Since it is possible for a fire to arise in the shaft, the reveal cover is to be attached over its entire surface and the requirements to the fire resistance of shaft walls and their penetrations apply both from the outside to the inside and from the inside to the outside. The shaft shall be partitioned horizontally between the basement and the first story above ground, as well as between the uppermost story and the attic. Gypsum is generally used as fire resistant boards.

- **Shaft type B**: The shaft is partitioned horizontally at every floor according to the requirements to the storey fire resistance. The partitioning system includes fire pipe collar, line section insulation, or similar devices. The floor does not need to be clad in the partitioning area. Wood surfaces that are exposed in the shaft must be clad with non-combustible material.

Vertical concrete walls might be employed to make the shafts, offering fire compartments and acting as shear walls at the same time. Services could run inside concrete hollow walls, which would become shafts themselves.
Horizontal canalisation in multi-storey timber houses is consistently assembled in the space between the ceiling and the floor element of the upper floor without considering the structural system. If the ceiling is not included in the floor element, the services can be placed in this space before making the finishing; instead, if the ceiling is integrated in the floor element, services are installed at the factory. For a system based on panel elements, the service layer can be placed either on top of the floor board, in case of floating floor, or underneath it in case of suspended ceiling. The choice of the solution is strictly connected to the sound insulation design (Swedish Wood, 2015).

The service systems can be integrated in the building in a similar manner for both concrete and timber structures; in timber buildings, special attention must be paid to the risks of cutting the fire insulation because of the penetrations between compartments generated by the service systems. Three methods of integration are here presented, depending on the fire separation and the desired interior finish (Green and Karsh, 2012):

- **CNC or route out chases** within the mass timber panels to receive all services: it is popular in Europe, but it requires a high level of pre-construction coordination and does not allow flexibility during construction.

- **Encapsulation approach to fire separation**: it provides non-combustible chases or cavities both horizontal and vertical to run services outside of the fire protection layer. It is a North American construction practice.

- **Charring approach to fire separation**: it provides a zone of services along the room’s floor perimeter in corridors and at doorways to run services and outlets (including a sprinklered cavity at the ceiling). This requires some pre-construction coordination but retains flexibility during the construction phase.
For easiness of making and flexibility in next modifications, the charring approach to fire separation (Figure 20) seems to be the most suitable option, also considering that the charring fire protection approach is the most accepted and used in timber construction practices. However, in any building (even concrete-only made) the concept of providing a zone of services along the room’s floor perimeter to run services and outlets shall be adopted to allow inspection and maintenance.

Many issues in integrating service systems in buildings derive from confusion on the great number of components; this would be even more problematic if there are both timber and concrete components. It should then be avoided the dependence of wholesalers on large catalogues; instead, it should be provided a set of standard module drivers for the building services, in order to design according to standard dimensions. The aim would be to build up traffic modules out of standardised components, which gathers all incoming media and distribute them to other parts of the dwelling (however, mixed configurations with electricity and water supply are advised against, since leakage problems cannot be guaranteed). Vertical and horizontal interfaces are designed after module driver specification; moreover, for the connection between modules, adaptation and tolerances must be considered. An additional advantage of modularizing the service systems is that, for example, some pipes can be plugged and activated if the building grows taller (Lennartsson, 2009).

Modularizing and standardizing timber and concrete products in accordance with integration of service systems would simplify on-site assembly, making it less time consuming and more efficient. This would require a revision of the purchase logic, i.e. the Builder-Wholesaler- Manufacturer chain, in the sake of collaboration and simplification. Once again, this emphasises the problems with regulations. For example,
for the Swedish case, building companies should be able to lobby against the Swedish National Electrical Safety Board, so that the responsibility is moved closer to the builder; in fact, since subcontractors are often bringing their own materials (which are part of the agreement), they would be glad not to find surprises and to have a standard design to deal with, instead (Lennartsson, 2009).

Even here, modularity is the answer to the integrated design: a good design of prefabricated concrete and timber elements that are compatible with a lean service integration would incentivize the hybrid construction market by attracting other stakeholders thanks to a smooth supply chain. The key is to identify and carefully design the interfaces. Besides the interfaces concerning the two materials, modularity would create prerequisites to improve interfaces between structural/architectural elements and services systems in terms of components, activities and actors.

From a process perspective, the process for building services can be broken down into isolated phases: activities are classified and clustered with respect to their characteristics, and are therefore better coordinated. Furthermore, the standardisation and the coordination of activities opens up the possibility for parallel production and assembly, aiming to lower the overall lead time. Moreover, there would be improvements in performing outsourcing strategy, isolating the actors in the supply chain, and purchasing materials with standardised bills for the modules (Lennartsson, 2009).

From a product perspective, the introduction of base modular shaft and ceiling including only necessary media and the interfaces prepared for additive submodules (Figure 21) would be a solution flexible to different arrangements of the floor service system. The placements of the interfaces between the shaft and the ceiling should be coordinated with respect to buildability, maintainability, and safety (Lennartsson, 2009).

![Initial 3D-visualisation of the proposed shaft and ceiling solutions (Lennartsson, 2009)](image)

*Figure 21. Initial 3D-visualisation of the proposed shaft and ceiling solutions (Lennartsson, 2009)*
3.4.5. Constructability

The process of construction is characterized by a great complexity and a vulnerable nature; schedules, resource limitations, multiple objectives, project uncertainties, business priorities and other inevitable variables and constraints make the operations very challenging. The main intent is to improve the construction business efficiency and productivity in terms of profitability and resource management (Hossain and Ruwanpura, 2010). Nevertheless, nowadays, a few construction firms have experience in undertaking timber building projects; however, erection techniques and tools (e.g. for lifting of panels) are often borrowed from the enduring precast concrete industry. In this perspective, the erection of a timber-concrete hybrid building would be simplified by employing machineries, equipment, and practices similar for both precast concrete and timber elements.

The focus on the constructability is important because the construction industry gets the major advances in the ease and speed of construction. The main issues to be considered are (PCI Industry Handbook Committee, 2004):

- limitations at the factory that may affect the method of fabrication;
- transportation from factory to construction site;
- limitations of the construction site for storage and movement of precast elements;
- ease of erection;
- connection details among both precast and made in-situ elements.

The constructability will be influenced by the location, size, and nature of the construction site, since the construction method of a timber-concrete hybrid building mostly made of precast elements is based on lifting procedures. In fact, the construction logistics aims to plan and control in an efficient way the flow of materials and activities among all the actors (especially suppliers and contractors), in order to optimize the decisions regarding the material supply and the site layout while minimizing the costs of ordering, carrying, and storing such materials (Said and El-Rayes, 2010). Then, factors like good accessibility and sufficient space to manoeuvre the crane and trail within the site are important. Size and weight of each precast component must also be carefully evaluated to facilitate handling and erection (Singapore Institute of Architects, 1999). The entire construction plan shall be thought early in the design stage; thus, a good coordination between architect, engineer and contractor is necessary. For example, time needed for the construction of cast in-situ concrete podium could be employed as lead time required for fabrication of precast elements.

**Constructability of Timber buildings**

All timber elements should be pre-fabricated to sizes suitable to optimize speed and ease of erection. In fact, the extensive level of design completed off-site helps to minimize site errors and to reduce the complexity of site management required. One thing to have in mind when fabricating the timber panels is the connection between elements. Usually steel fasteners are used, but sometimes special connections are required and panels should be provided, already in the factory process, with a predisposition for the specific connection. Annex B provides an overview of the EWPs’ common connections types.

One problem of the timber panels is the space required for the transportation and manoeuvres on site, particularly in urban context. This is a problem regarding any prefabricated elements, but timber panels could be easily divided in sub-modules with sizes that suit the space restrictions (by following the prescription mentioned in Annex A). In the construction site, also space for storage should be considered. In the case of
the wood special attention should be payed to protect the products from the detrimental exposure to water and weathering, until the elements are installed and the finishing are completed.

Usually timber buildings are assembled through lifting of the elements; a great advantage, compared to the assembly of precast concrete products, is that less powerful machineries are required, thanks to the light weight of the timber products. Thus, bigger elements like entire modular boxes, can be easily lifted; also, several panels can be assembled together on the ground and then lifted-up to build several storeys at a time. Thanks to the easier manoeuvres compared to concrete case, many alternative and original lifting solutions are possible, like the use of helicopters. Finally, lifting inserts are similar to the ones used for precast concrete elements (e.g. lifting loop threaded sleeve, threaded eyelet bolt, soft lifting sling, screwed anchor, screwed plate and lifting ring, inserted rod, etc.) (FPInnovations, 2011).

An issue that always affects the erection of timber building is the need of temporary bracing, which becomes especially problematic when panels are required to be braced on the exterior side, since more space is required in construction site. On the contrary, temporary bracing can be normally avoided in concrete structures. It is envisaged that the core would be erected first and used to brace other walls and columns, working from the inside out. Alternatively, the core can be pre-assembled on the ground and erected in 3 or 6 storey lifts (Figure 22). Moreover, during erection, temporary roofs are used to protect apartments, joints and timber from water and other weather actions, until the finishing are completed (Green and Karsh, 2012).
Step 1
1 install inner core walls (first lift)
2 scaffold inner core to access connections
3 brace inner core walls until core walls are secure

Step 2
1 install outer core walls and brace
2 brace outer core walls until floors are in
3 install floors and remove braces

Step 3
1 low lift exterior walls
2 brace exterior walls

Step 4
1 install steel beams connecting to core to outer walls
2 remove braces

Step 5
1 low lift remaining two side exterior walls
2 install floors
3 brace until four exterior walls are connected and floors are in

Step 6
1 second lift inner core
2 brace inner core all inner core walls are secure
3 brace outer walls
4 will require lift on floor 6 to access connections

Step 7
1 second lift outer core walls and floors
2 brace outer core
3 install core floors
4 will require lift on floor 6 to access connections

Step 8
1 second lift outer walls
2 brace walls
3 repeat steps 4,5

Figure 22. Example of erection of a mass timber building (Green and Karsh, 2012)

A typical advantage for timber building construction is that once a floor in a building has been completed, it will be available for bearing the upper floor immediately. The concrete frame, if prefabricated, does not require back propping under each newly poured floor, but some limitations of the speed of the building erection derive from the time required for the precast elements to achieve their full strength. In general, the delay is related to the core construction (three or four weeks), which is propped on-site, but sometimes it can be precast as well or it is not necessary at all.

Constructability of Precast Concrete Buildings

As for timber elements, production of precast concrete elements is subject to manufacturing and alignment tolerance; however, a careful production planning is here necessary due to moulding; for example, time of construction of each floor of the building is a key factor in estimating the number of precasting moulds; it should be considered that at least one month and a half is needed for manufacturing the moulds and half a month for the production of the precast units. Therefore, the precast shop drawing should be consolidated at least two months in advance of the scheduled date of delivery to site. Moreover, the production of the concrete needs pre-concreting check: the condition of the mould should be inspected since it directly influences the quality of the precast concrete product. Also, reinforcing bars and cast-in items (such as lifting inserts and window frames) are to be allocated in the mould (Singapore Institute of Architects, 1999).

Precast concrete products can only be demoulded and lifted when they have achieved enough strength; in fact, when the newly cast element is lifted from its casting bed or formwork, it will be subjected to self-weight and demoulding forces caused by adhesion with the formwork. Also after demoulding, dynamic loads and impact forces during handling, transportation and erection of precast elements should be accounted by applying a load factor to the self-weight of the element. In fact, contrary to timber, concrete has different
strength levels depending on the degree of maturity, and the gained strength should be evaluated in each stage of construction (Singapore Institute of Architects, 1999).

As for timber, delivery of precast elements, including loading, transportation and unloading, should be properly planned so that unnecessary site storage and handling is minimized. Precast concrete elements can be damaged by incorrect stacking and storage. Therefore, supports must be arranged to avoid twisting or distorting of precast elements and must be adequate to transfer the weight of the stacked units to the ground without excessive settlement.

Also in this case, when transporting the units, it is important to observe the transportation regulations. Moreover, once the units have been loaded onto the vehicle, they shall be firmly attached to the supporting members and fastened with a position locking device to ensure that they are not subjected to undesirable stresses due to flexing of truck. Once reaching the construction site, precast concrete components should be stored in a vertical position similar to their final position in the building. However, precast walls and façade panels are usually cast horizontally and rotated for storage in upright positions with racks and stabilizing walls to support their weight. (Singapore Institute of Architects, 1999) Planning the storage sequences for site erection (including the rigging sequence and method) becomes even more important compared to timber panels, because multiple handling of precast elements would be more complicated. Using modular and standard products can help to reduce mistakes in planning the storage: it would be easier to manage repetitive unites, which could also be interchanged and replaced.

Being prefabricated, precast concrete elements are assembled by lifting. Lifting hooks and inserts must be carefully assessed in relation to their bearing capacities and the precast components, in order to optimize the number and locations of lifting inserts. It is also necessary to evaluate the possibility to lift and handle the precast elements before they gain their full strength. There are several types of lifting equipment and accessories such as supports, frames, blocking, cushioning and tie downs, or also combinations of lifting beams or frames and slings. More specifically, there are reinforcement bar with omega “Ω” shape lifting insert (used in thin precast elements), lifting anchor with bulky head or with eye for reinforcement bar, lifting clamps, straps or slings (for some precast elements like hollow-core floor slabs, which do not have lifting inserts). Lifting procedures and devices shall be aimed at ease of erection and connection of the precast units in the building structure. Also in this case, standardization of lifting devices installed in various precast elements would avoid frequent changes of lifting methods. Locations of lifting devices and lifting points shall be compatible with the method of shipment so that patching and repairing would be minimal (PCI, 2007). Generally, timber panels are already being lifted with the same devices and techniques of precast concrete elements: the advantage is that timber is much lighter than concrete; thus, less performant tools are required.

While assembling the precast concrete units, structural action and load paths during the temporary stages are different from those at the permanent stage. Precast elements supporting upper levels shall be checked against their concrete strengths gained at that stage to ensure they are able to sustain the construction loads from above. Provision should be made for both the panel and the support system to allow immediate temporary bracing of the panels. The temporary bracing must be maintained until permanent connections are achieved (PCI Industry Handbook Committee, 2004).

Safety measures should apply from the first lift out of the mould until the component is permanently installed in the construction. For both concrete and timber prefabricated elements, the absence of peripheral
scaffolding in precast construction is a major difference from conventional construction. In fact, the costs for cleaning, site hygiene, scaffolding and staging can be very significant for cast in-situ projects.

Building made of prefabricated elements should be carefully planned in advance, since patching and repairing during construction are not so easy as for cast in-situ concrete. Therefore, adequate tolerance is essential to avoid irregularities such as tapered joints (panel edges not parallel), movement at intersection and non-uniform joint widths. During the production, the prefabricated elements are inevitably affected by variations in their sizes; in phase of assembly, these dimensional inaccuracies lead to a cumulative effect that may affect the quality of the entire structure; this can be prevented by carefully planning and providing enough tolerance in the assembly plan of the prefabricated elements (PCI Industry Handbook Committee, 2004).

Usually precast concrete is employed to optimize speed, quality, and flexibility in construction of multi-storey buildings, especially those having regular shape, large structural span, and bearing high load. The typical frame of the structural system has a primary direction (7.5-10 m) and a secondary direction (10-20m). Usually, the system is self-supporting and thus it does not need temporary support props (Figure 23 and Figure 24). The system includes (Sicep Tunisie, 2017):

- monolithic pillars, stuck to the foundations and provided with shelves in correspondence of the floors;
- main beams laying on the shelves of the columns;
- floor elements placed on the largest span, laying on the main beams and connected through a 10-15 cm cast on-site cement layer;
- secondary beams placed on largest structural directions.

![Figure 23. Construction sequence for multi-storey building made of precast concrete elements (Singapore Institute of Architects, 1999) (continuation on the next page)](image-url)
Columns erection (figure above):
1.1 Erect columns
1.2 After the grout for the column base and connection has reached enough strength, dismantle the push and pull prop

Construction of the one floor (figure below):
2.1 Erect temporary props on floor
2.2 Erect main beams with cranage on to the corbel of columns
2.3 Install steel shims or wedges between temporary props and main beams to ensure the support
2.4 Erect the double tees on the main beam with cranage
2.5 Fix rebar and cast in situ topping

*Figure 23. Construction sequence for multi-storey building made of precast concrete elements (Singapore Institute of Architects, 1999)*

Besides columns, beams, and slabs, also wall panels need to be erected; this operation is delicate for both load-bearing walls and façade panels, since they could reach 10 tons in weight. Their installation (Figure 25 and Figure 26) includes difficult steps like lifting, temporary bracing, and adjusting with tolerance (especially when a floor should be loaded on it) Prefabricated staircases are also critical for the constructability of buildings; their installation is a delicate operation and requires to construct first the supporting beams and landing, then to lift the staircase and lower it on the supporting members; props are usually required and can be removed just after the joints gain strength (Singapore Institute of Architects, 1999).

In installing the precast elements, the most delicate operation is the realization of the joints: The vertical joints between the panels should be provided with a certain tolerance gap (usually 10mm ± 2mm). Gaps shall be also left between the beam (or ceiling) and the top of the partition (about 25mm) and between the structural floor and the bottom of the partition (not more than 35mm). In general, the permanent connections shall be made before the partitions are erected and aligned; afterwards, the joints shall be patched up with non-shrink grout, and some mild steel fasteners (dowel bars or angles) shall be installed to secure the wall panels to the ceiling according to the rate that best suits the desired level of ductility (Singapore Institute of Architects, 1999), similarly to what said for timber structures.
1 Lift the precast façade from storage to desired working position
2 Install the inclined temporary bracing and toe bracket
3 Adjust the panel to its final level onto the top of the bottom façade panel
4 Fix steel reinforcement of the adjacent wall
5 Install the framework to the wall
6 Concrete the wall
7 Dismantle the temporary bracing
8 Construct the floor slab

Figure 25. Installation of precast façade panels (Singapore Institute of Architects, 1999)

1 Align the precast panel in desired position, allowing for skimming to flush with the adjoining reinforced concrete structure.
2 Secure the panel by means of mild steel angles and expansion bolts
3 Erect and fix the panel into required position by fitting the top angle into the recess/gap and held on firmly by timber wedges.
4 Fix a galvanised L-shaped steel plate to the bottom of the first and last panels.

Figure 26. Installation of a precast lightweight panel (Singapore Institute of Architects, 1999)

3.5. Operation and maintenance

To evaluate an innovation within the construction market, it is important to consider how it will perform during time. Since a few examples of timber-concrete hybrid buildings exist over the world and they represent stand-alone and exceptional cases, it is necessary to make a guess on how a hybrid building will perform by referring to concrete-only and timber-only buildings and combine their relative experiences. Several interacting factors influence the long-term performance of a building (Bejrum 1987).
- physical characteristics and technical design (e.g. age, size and height, type of structure, finishes, services, construction materials);
- condition and modernity of the building;
- utilization and occupancy (continuative or alternative);
- geographical location;
- strategy, organisation and owner’s attitude;
- institutional framework: laws, regulations, norms and common practice.

Regarding operation, comfort, and aesthetic by the end user perspective, most of the people perceive timber as a warm and comfortable material pleasurable to be in touch with. Vancouver architect Michael Green, who is the main promoter of tall wooden buildings, claimed: “I’ve never seen anybody walk into one of my buildings and hug a steel or a concrete column. But I’ve actually seen that happen in a wood building” (Stamp, 2016). On the other hand, one could perceive concrete as a strong, durable material that counteract the “weakness” of the timber in building. Although many people see concrete as a cold material, the union with wood in a hybrid structure could enhance an impressive combination of feels of strength and cosiness.

However, both concrete and timber should be preserved from deterioration, although the characteristics of durability are different from each other. These differences can be exploited to allocate concrete and timber in the most suitable place, to fulfil complementary functions and better withstand the specific causes of deterioration. Information on the durability of both concrete and timber can be found in Annex B; however, below is presented a short summary about the durability of wood and concrete.

The deterioration of the wood might be caused by biotic agents (biodeterioration) or abiotic agents like weathering, fire, chemicals and mechanical actions (e.g. long-period loading, abrasive actions from sand and water). The main concern for wood is to prevent the grow of microorganisms, like mould and hyphae-growing decay fungi (which cause rot and consecutive loss of material). About thermal degradation, it should be considered that the wood does not burn instantaneously, since a char layer is formed first. There are some good design practices capable to assure the protection and the long-term performance of the timber products: wood can be preserved through treatment with toxic chemicals, through modification, or through physical barriers (e.g. coatings); the main function of this last protection method is to keep water away from the structure.

Durability of concrete is determined by the transport of aqueous and gaseous substances in the pore system and their interaction with the paste matrix, the aggregate, or the steel reinforcement. Indirect degradation is caused by carbonation-induced corrosion or chloride-induced corrosion of the reinforcing steel. Direct degradation is caused by freeze-thaw attack, reactivity of aggregate and/or of the cement paste, or acid action (fédération internationale du béton (fib), 2013). To ensure the durability of concrete during its design life, it is necessary to specify a suitable concrete mix and to provide sufficient concrete cover. The right mix reduces the permeability of concrete, whereas coatings protects the concrete against chemical attacks, controls water penetration, and prevents some physical damage (Woodson, 2009).

To ensure a good long-term performance for the entire building, it is important to carry out frequent inspections and continuous maintenance. The concept of providing a zone of services along the room’s floor perimeter to run services and outlets, perhaps inside timber cases designed according to the charring approach (refer to section “2.6.4. Building service systems”) would enable easy inspection and replicability of the services. Having standard and modular shafts that are not cast in situ and tailored, but prefabricated
and standardized, would also help to have easy access to the service and eventually replace them. In general, using components that are designed as removable would allow the replacement of the deteriorated elements.

The standardisation of products means an incentive to the open system within the construction industry and therefore a push to the interchangeability of the construction components, both within the timber items themselves and between the timber and concrete items. In this perspective, a hybrid building would be made of elements in some extent easy to replace when needed, especially for the partitions and the external envelopment and cladding. It is here that the potentiality of the standard, modular prefabricated market should be exploited, especially in timber, which is easy to manoeuvre and assemble.

To conclude, a reflection can be made on the Swedish context. Although in Sweden there is an increasing trend towards off-site production in housing, this is limited to the detached house market, whereas the multi-storey buildings represent only the 15% of market share. The reason is that the client lacks confidence in whether the system will have an optimal life cycle performance (Höök, 2005). However, some studies conducted by benchmarking similar timber and concrete buildings reveal that running costs for the two types of buildings have just a light difference, confuting the general opinion that timber buildings have higher running costs (the concern is especially about the energy expenditure for heating). In general, the factors primarily affecting the running costs in timber buildings are: number of floors (increasing height leads to decreasing cost); size of buildings (increasing floor area leads to decreasing costs); and type of owner (Levander and Sardén, 2009).
4. Results and discussion

Timber-concrete hybrid innovations - A framework to evaluate economical and technical factors

When speaking about timber-concrete hybrid construction, it is important to evaluate the possibility to introduce such an innovation into the EPC market. Since dealing with a business strategy, besides the technical aspects, some important Market Selection Criteria related to timber-concrete hybrid construction should be considered to build up a wise and a complete decision-making framework (Table 8, also refer to section “2.4.3. Market Indicators”). These criteria are flexible and practical to assist market decisions based on industry-level analysis, and should be evaluated in connection to the overall context.

<table>
<thead>
<tr>
<th>Table 8. Economic factors related to timber-concrete hybrid construction</th>
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<tbody>
<tr>
<td>Demographic environment</td>
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<tr>
<td>• Population age and gender segment</td>
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<td>• Income distribution</td>
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<tr>
<td>• Infrastructure</td>
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<tr>
<td>• Geographical/physical distance</td>
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<tr>
<td>• Human resources</td>
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<tr>
<td>Economic environment</td>
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<tr>
<td>• Market growth/development</td>
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<tr>
<td>• Market consumption, middle class</td>
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<tr>
<td>• Economic freedom</td>
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<tr>
<td>• Long term market potential</td>
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<tr>
<td>• Investment incentives, tax advantages:</td>
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<tr>
<td>• Financial risk factors</td>
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<tr>
<td>Social-cultural environment</td>
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<tr>
<td>• Cultural distance, psychic distance</td>
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<tr>
<td>• Education level</td>
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<tr>
<td>Sector/product-specific indicators</td>
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<tr>
<td>• Competitive landscape</td>
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<tr>
<td>• Customer receptiveness, demand potential</td>
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<tr>
<td>• Personal and social values of consumers</td>
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<tr>
<td>Firm-specific indicators</td>
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<tr>
<td>• Strategic orientation of the firm</td>
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<tr>
<td>• Network relationships</td>
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<tr>
<td>• Motivations for growth and reputation</td>
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</table>

However, as an industrialized solution, it is fundamental to consider the technical factors related to the timber-concrete hybrid constructions, still with a holistic perspective (Table 9). To do that, the building could be considered as an assembly of modular units (Figure 27), the size of which should be set according the standard dimensions suggested within the modular planning and the standardization of the products (see Annex A); thus, the dimensions of the modular units can vary by multiples of 60 cm for the width (also sub-multiples of 30 cm are possible) and multiple of 5 cm for the length and the height. This division of the building design into modular units applies to different types of structural systems: post and beam structures, platform structures, prefabricated volumetric modules, etc. To have a preliminary overview of the entire building system, these modular units can be considered as independent units useful to roughly evaluate the structural design, fire protection, energy and IEQ performance, building service systems integration, construction plan, and cost (Figure 28).
Table 9. Technical factors related to timber-concrete hybrid construction

| Lateral Load Resisting System | • Bracing prevents lateral and torsional displacements caused by wind and earthquake. • Shear forces are transferred from the roof and floor diaphragms to the vertical bracing system (like shear walls) and onto the foundations via a system of connections. Diaphragms distribute the horizontal forces to the supporting vertical structures in proportion to their relative rigidity R. • Types of bracing: diagonal bracing, shear walls, rigid joints • Typical LLRS: core walls and headers; perimeter wall moment frames; interior partitions (complement for the primary LLRS) • Tall buildings: necessary to assure stability and good comfort in higher storeys against possible horizontal deformation |
| Vibration | • Vibrational modes depend on stiffness and mass and their distribution. Light weight of timber constructions leads to wind induced vibration, thus discomfort of the occupants. • Solutions: distribute the mass (concrete topping on floors); stiffness (permanent internal solid wood); stiff concrete basement |
| Fire protection | • Different regulations depending on the country; common practices in handbooks • Compartmentation: limitations in height for timber • Timber: charring or encapsulation approach |
| Building Technology Details | • Stratigraphy of floors, partitions, external walls, connections • Energy performance of the building: thermal loads determined by climate context (e.g. external environment temperature, external relative humidity, exposure to the sun); properties of the materials (e.g. thermal conductivity and thermal inertia) • Indoor Environment Quality: release of compounds, ease in cleaning surfaces, psycho-physical conditions of the occupants • Design of details. Concrete: strong know-how and a broad set of normal practices. Timber: many technologies built up basing on the equivalent existing concrete solutions; some particular aspects like fire protection, thermal performance, acoustic, vibration, weather protection |
| Building Service System | • usually subordinated to the structural system • Integration of service systems in the building similar manner for both concrete and timber structures and strictly connected to industrialised timber-concrete housing • base modules shaft and ceiling and their interfaces prepared for additive submodules: flexible for future rebuilding, maintainability, and safety • Timber: attention to fire insulation of service cases. Three methods of integration: CNC or route out chases within the mass timber panels receiving all services (high level of
pre-construction coordination, no flexibility during construction); encapsulation approach to fire separation (non-combustible chases or cavities to run services outside of the fire protection layer); charring approach to fire separation (zones of services along the room’s floor perimeter to run services and outlets; this solution requires some pre-construction coordination, but retains flexibility during construction).

- **Smooth supply chain**: possibility to isolate phases for better coordination, parallel production and assembly, and outsourcing

| Constructability | • Main issues for ease and speed of construction: limitations at the factory; transportation from factory to construction site; limitations of the construction site for storage and movement of precast elements; ease of erection; connection details among both precast and made in-situ elements
|                  | • Construction plan conceived early in the design: good coordination between architect, engineer and contractor
|                  | • a few construction firms have experience in undertaking mass timber building projects; machineries, equipment, and practices similar for both precast concrete and timber construction.
|                  | • Handling of prefabricated elements: accessibility and manoeuvring depending on elements’ size and weight; location, size, and nature of the construction site; difficult to manoeuvre: panels could be reduced in sub-modules. Concrete: heavier; dynamic loads and impact forces during handling, transportation, and erection of precast elements; different strength levels depending on the degree of maturity. Timber: lighter
|                  | • Production (prefabrication). subject to manufacturing and alignment tolerance, extensive level of design completed off site, speed and ease of erection, minimization of site errors. Precast concrete: careful production planning of moulding (estimation of time, pre-concreting check, reinforcing bars and cast-in items); demoulding forces. Timber: connection among elements (steel fasteners, special connections requiring predisposition in panels)
|                  | • Transportation. Traffic regulations. Concrete: heavier; elements carried on supports and fastened to avoid undesirable stresses. Timber: lighter
|                  | • Storage. Concrete: elements on supports to avoid twisting or distorting and transfer the weight to the ground; stored in position similar to the final position in the building; careful planning of storage sequences because of the difficult handling of elements. Timber: protect the elements from water and weathering
|                  | • Lifting: methods similar for timber and precast concrete elements; lifting devices shall be standardized to avoid frequent changes of lifting method. Concrete: heavier (high performance machineries); evaluate the possibility to lift elements before they gain the full strength. Timber: lighter (low performance machineries); bigger elements (boxes) can be lifted; pre-assembly of panels on the ground before lifting; easier manoeuvres allow alternative lifting solutions (e.g. helicopter).
|                  | • Temporary bracing. problematic because space demanding. Concrete: not always necessary (if required, it must be maintained until permanent connections are accomplished). Timber: always necessary
|                  | • Erection. Precast Concrete: elements supporting upper levels shall be checked against their concrete strengths gained to ensure they are able to sustain the structural loads from above. Timber: once a floor has been completed, it will be immediately available for bearing the upper floor

| Operation and Maintenance | • Factors influencing long-term performance: physical characteristics (age, size, height, structure, finishes, services, materials); condition and modernity; utilization and
occupancy; geographical location; owner's attitude; institutional framework (regulations, common practice)

- **Comfort**: timber generally perceived as warm and comfortable, but weak; concrete generally perceived as cold but strong, durable

- **Durability**. *Wood deterioration*: biodeterioration (mould and hyphae-growing decay fungi) or abiotic agents (weathering, fire, chemicals and mechanical); *Wood design practices*: chemicals treatment, modification, physical barriers (coatings as covering steel plates and protective weathering panels; keep water away from the structure)

- **Concrete deterioration**: transport of aqueous and gaseous substances in the pore system and their interaction with paste matrix, aggregate, or steel reinforcement; Concrete design practices: specify a suitable concrete mix and to provide sufficient concrete cover.

- **Inspections and maintenance**: services along the room’s floor perimeter, perhaps inside timber cases (see “charring approach” pg. 35); standard and modular shafts (not cast in situ, but prefabricated): easy inspection and replicability of the service

- **Standardisation and replaceability**: standardisation of products means open system: both timber-timber components interchangeability and concrete-timber components’ interchangeability

- **Running costs**: lack of confidence in timber buildings’ life cycle performance; factors affecting the running costs in timber buildings: number of floors (decreasing cost with increasing height); size of buildings (decreasing cost with increasing area); type of owner

---

Cost*  

- **Structure**: *Foundation* (made of concrete; for a timber building it would be smaller because of the lighter overall weight of the building; the economic advantage increases as the building becomes taller); *Basement excavation* (unchanged); *Lowest floor construction* (unchanged); *Floor construction* (higher cost for wood, but the difference of cost becomes smaller as the building becomes taller, due to the ease of lifting of timber and the difficulty in propping the concrete in height); *Stair case* (not convenient in wood; increase of cost ~ 35%); *Roof structure* (not convenient in wood, increase of cost ~ 65%; concrete is better also to lower the vibration)

  *Note*: the comparison of the costs between the timber and the concrete structures above basement refers to a structural system made of columns and slabs, where the timber-concrete benchmarking is possible. Typical timber structures (as the platform construction) may exploit better the structural capabilities of the timber.

- **Exterior enclosure**: *Curtain walls* (thermal insulation and weathering cladding depending on the climate context); *Windows, glazed screen, doors, roof covering, skylights’ projections* (unchanged)

- **Partitions and doors**: *Floor and Wall Partitions* (encapsulation timber more expensive because of additional wallboard, increase of cost ~ 75%; charring timber, unchanged); *Structural partitions* (no need of core in low rise building, solid timber core walls convenient in medium rise building; lower convenience as the building becomes taller. *Ceiling finishes* (encapsulation of timber more expensive because of additional wallboard, increase of cost ~ 100%; charring timber, unchanged)

- **Mechanical (unchanged)**: *Plumbing and Drainage, Fire protection, HVAC, Controls*

- **Electrical (unchanged)**: *Service and Distribution, Lighting, Devices & Heating, Systems and Ancillaries*

- **General requirements and fees**: *General Requirements* (timber construction is quicker, decrease of cost ~ 15%); *Fees* (lower by using timber, decrease of cost ~ 40%)

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*data inferred from the case study of the pilot project “Tall Wood”, where the same building has been designed by benchmarking concrete and timber construction options and by varying the structure according to the height of the building and the alternative between encapsulation design and charring design (Green and Karsh, 2012).

The modular units of the building can be broken down into several functional systems to be evaluated according to structural design, fire protection, energy and IEQ performance, building service systems integration, construction plan, and cost (Figure 28). This approach would make easy to choose within timber and concrete products to use in the building, according to a holistic perspective.

**Figure 28.** Modular units broken down into several functional systems to be evaluated according to different construction parameters.

**Foundations**

Concrete is the only alternative for several reasons:

- Optimal behaviour in compression
- High durability in ground (yet, some precautions needed)
- Stiffness for LLRS
- Stiff basement to lower vibrations in upper floors

**Horizontal Load Bearing System**

- **Structural design**
  - Concrete/timber beams (both fail in tension) together with unidirectional floor slabs
  - FRC bidirectional slabs are good for tension strength and impact/blast strength
Timber (CLT/LVL/OSB) bidirectional slabs are lighter
Floors require infinite in-plane stiffness to carry horizontal loads and transfer them to the vertical load bearing system, and to the foundation. They should be well connected to the frame to transfer the shear: for cast in-situ concrete floors, monolithic connections with the frame; for precast concrete floors, attention to dry connections (simply supported); for timber floors, sheathing-to-framing joints, connections and damping design ensuring the right degree of ductility (nails or slender screws with steel brackets to connect the walls to the floor below have low ductility and lead to brittle failure; studs must be well connected to foundation)
Timber elements have problems with vibration: concrete topping to add mass and lower the vibration
Fire protection
High number of timber floors are limited by dispositions on fire compartmentation (e.g. 4 floors for Austria, 12 for Canada)
Concrete floors, especially glass FRC have good fire insulation performance and can be used for compartmentation
Floors should ensure a minimum level of load-bearing capacity R against the fire. Concrete floors: good performance; timber floors: charring method (sacrificial thickness), encapsulation method (layers of fire-rated gypsum board, expensive)
Design of building technology details
Timber floors have problems in acoustic (need to be decoupled)
Flexibility in terms of options for timber floor assemblies: rather independent from the floor system (various EWPs can be chosen)
Timber design more influenced by vibrations and deflection, fire resistance, sound performance and integration with services.
Sound insulation: decoupling floor and ceiling; subfloor (approximately the same total floor thickness)
Composite floors: made of timber and concrete. Good technical performance, but quite expensive; timber in tension and concrete in compression
aesthetic aspect of timber floors for a wood bottom view
avoid sound bridges towards the screed near walls, supports, installations
Building service systems integration
Allocated in the ceiling; if the ceiling is integrated in the floor element, services are installed at the factory
ceiling need to be protected from fire; ensure airtightness in the area of electric installations. Hollow concrete slabs can be used to allocate service systems, and protect from fire
solution is strictly connected to the step sound insulation: on the top in a floating floor, or in suspended ceiling.
Construction plan
if prefabricated, beams and slabs have higher quality and are faster to build, especially if made of timber (lighter)
Cast in-situ concrete have rigid joints; for prefabricated elements attention to connections and tolerance in the allocation of the floors onto the beams or the columns
Cast in-situ floors are slower to produce compared to vertical elements (easier to prop)
Precast concrete floors are heavier and more complicated to lift than timber floors
Timber: once a floor has been completed, it will be immediately available for bearing the upper floor; prefabricated concrete: limitations on the speed of erection derive from the time required by the floors to achieve their full strength; cast in-situ concrete: propping on-site leads to delays.

Vertical Load Bearing System
Structural design:
concrete works very well in compression: concrete columns suggested.
timber works well in compression parallel to the fibre direction (but not as good as in tension): plastic behaviour at high loads
concrete/EWPs loadbearing walls; premade openings are easier to make in timber rather than in concrete.

- Bracing system: diagonal bracing, shear walls, rigid joints. Lateral Loading Resistant System (LLRS): core; perimeter wall moment frames; interior partitions (complement for the primary LLRS).
- Stabilisation forces (received from the floors) should be spread to as many shear walls as possible. Cast in situ concrete: generally, no bracing needed (rigid connections and good in-plane stiffness). Timber: skin-framed structure rather flexible, thus lateral strength and stability provided by shear walls (sheathing-to-framing joints necessary).
- LLRS solution must be a monolithic piece from the foundations to the roof; cast in situ concrete generates monolithic piece (paying attention if cast in several layers); prefabricated concrete/timber panels must be properly connected to create larger wall panels.

- **Fire protection**
  - See “Inner partitions”

- **Design of building technology details**
  - See “Inner partitions” and “External Envelopment.”

- **Building service systems integration**
  - See “Inner partitions”

- **Construction plan**
  - Temporary bracing. Cast in-situ concrete: generally, not needed because of monolithic frame, precast concrete might need bracing until connections are finalized. Timber: always needed.
  - If prefabricated, columns and wall have higher quality and are faster to build, especially if made of timber (lighter).
  - Vertical elements. Cast in-situ concrete: quite easy to prop; monolithic piece. Precast concrete: difficult to lift, allocate and connect. Timber: easy to lift (also possible to preassemble on ground and then lift), allocate and connect.

**Building envelope**

- **Structural design**
  - Can be used as loadbearing walls, loss of flexibility.
  - LLRS: perimeter wall moment frames; spread the stabilisation forces to as many walls as possible. Shear walls: ensure good connections with primary LLRs elements (sheathing-to-framing joints in timber). See “Vertical load bearing system”

- **Fire protection**
  - Ensure escape routes.

- **Design of building technology details**
  - Vapor retarder: EWPs in general work as moisture barrier.
  - Air tightness: EWPs assure air tightness, but a flow-tight sheet can be added for passive house.
  - Sound insulation: need of structural separation and insulation for timber.
  - Heat insulation: EWPs provide quite good heat insulation by themselves, but depending on the external environment insulation materials must be added. Attention to thermal bridges and the impact of element joints in prefabricated elements.
  - Storage-effective mass: decorative wood constructions or direct claddings increase storage-effective mass.
  - Durability of concrete and timber.
  - Aesthetic.

- **Building service systems integration**
  - See “Inner partitions.”
• **Construction plan**
  - Lifting the panels, for timber much easier than concrete
  - Erection: depending whether the façade is loadbearing or not, easier for timber
  - Precast concrete panels are more difficult to align bracing and connect than timber panels
  - Timber panels easier to replace than concrete panels (in case of non-loadbearing façade)

**Inner partitions**

• **Structural design**
  - Can be used as loadbearing walls, loss of flexibility for building uses
  - Bracing: inner partitions as complement for the primary LLRS. Spread the stabilisation forces to as many walls as possible. Shear walls: ensure good connections with primary LLRs elements (sheathing-to-framing joints in timber). See “Vertical load bearing system”
  - Timber elements have problems with vibration: permanent internal solid wood can help adding mass and stiffness

• **Fire safety**
  - Fire compartmentation (e.g. 1200 m² for OIB Austria)
  - Concrete walls, especially glass FRC have good fire insulation performance and can be used for compartmentation
  - Walls should ensure a minimum level of load-bearing capacity R against the fire. Concrete walls: good performance. Timber walls: charring method (sacrificial thickness), encapsulation method (layers of fire-rated gypsum board, expensive)

• **Design of building technology details**
  - Timber: sound insulation is an important requirement: gypsum boards on one or both sides. Single-leaf wall: completely decoupled shells on both sides. Double-leaf wall: space between the leaves filled up with stone wool for sound insulation (also fire protection).
  - Timber: do not install pipes through the wall
  - Airtightness of joints, connections and installations
  - Timber as an aesthetic supplement for the rooms

• **Building service systems integration**
  - Favourable multiple vertical shafts, large number of horizontal pipes can be avoided. Timber: due to the easiness of making openings on site, in general shafts are not prefabricated, canalisation and shaft assembly is made on site
  - Vertical concrete walls might be employed to make the shafts (acting as fire compartments and shear walls at the same time). Services could run inside concrete hollow walls
  - Fire insulation in timber shaft: cover attached over its entire surface for both sides, or shaft partitioned horizontally for every floor

• **Construction plan**
  - Timber, easy to rearrange the plan (flexibility) replaceability and interchangeability
  - Timber walls easier to lift then precast concrete walls

In synthesis, this study has put in evidence that, since hybrid construction does not represent a mere technical issue, it is important to carefully evaluate the feasibility of such business strategy within a specific context. To help with this economic evaluation, several market indicators have been detected. Among the principal indicators, there is the “Environment”, which evaluate - for example - the availability of wood in a certain area (Geographical/physical distance), and the presence of Human resources, like designers and builders, able to deal with the new construction techniques. Regarding the “Economic environment”, the main concern on employing timber in a construction solution is the lack of standardization and regulation within the new construction practices (Market growth/development); on the other hand, Investment incentives and tax advantages within an environment-friendly global policy could encourage the firms to move towards the hybrid solution, although the Financial risk factors in undertaking such innovation are
considered as high. Neither it should be neglected the “Sector/product-specific indicators” like Customer receptiveness, Demand potential and Personal and social values of consumers, which regard the perception of the people about timber-concrete constructions. Finally, the hybrid solution could be a way for the firm to differentiate its market within the Competitive landscape; this would mean to evaluate the “Firm-specific indicators”, like Strategic orientation of the firm, Network relationships, and Motivations for growth and reputation, which represent the predisposition of the parties to undertake new strategies and to deal with new dynamics within the supply chain.

Concerning the technical side, the presented method provides a preliminary evaluation, showing how to build up a timber-concrete hybrid by dividing the building into modular units and focusing on the main systems (horizontal loadbearing system, vertical loadbearing system, external envelopment, and inner partitions), while considering the technical aspects and allowing a direct comparison between timber and concrete solutions, especially regarding material properties (strength, durability, etc.), structural issues (lateral stability, vibration), fire protection, building technology details, building service systems integration, construction plan, and costs. In general, a material cannot in absolute terms be considered better than another, but much depends on the context in which it is produced and used and on the function that it should fulfil. Moreover, construction materials are often employed in their basic form and many potentialities are lost because value added products are unknown or are not explored, due to the fixed nature of the EPC industry.

The general framework here proposed to evaluate timber-concrete hybrid construction according to economical and technical factors is suitable to conform to each specific case, time after time. Referring to the Swedish context, a simple and standard timber-concrete hybrid solution seems to suite well to the regular multi-storey buildings typical of “Miljonprogrammet” (Eng. Million Programme), which have represented the outbreak of the concrete market in the 70s (Wikipedia, 2017). The hybrid solution can be seen as a reinvention of this kind of buildings, considering that – being made of repetitive precast concrete units - they are characterized by regular shape prone to modularity and standardisation and by the possibility of easy design and construction (Figure 29). Such a move would represent a possibility to expand the timber construction industry to a large type of buildings, and thus to a large segment of market; moreover, the need to restyle and give worth to “Miljonprogrammet” houses would affect positively the reputation of timber constructions in Sweden.

Figure 29. Typical multi-storey building in Sweden (left), prone to the modularization and the remake with standardized timber products (right)
(source: (left) https://hiveminer.com/Tags/bred%C3%A4ng,stockholm/Interesting; (right) https://www.proremodeler.com/boise-cascade-engineered-wood)
5. Conclusions and recommendations

5.1. Conclusions

The innovations within the EPC market are often hindered by the fear to undertake a high-risk project; at the end of this study, it is possible to answer the research questions posed at the beginning, in order to reach more awareness on the issues related to the timber-concrete hybrid construction.

• **What are the main economic and technical factors to consider in order to exploit the advantages of two different materials like concrete and timber and obtain the best synergy from them?**

To answer this question, a theoretical framework based on principles of lean construction and modularity has been developed, with the scope to detect the main issues related to the decision-making process of the timber-concrete hybrid solution, wisely exploiting all the advantages given by the two materials and always referring to the specific contexts and stakeholders.

• **How is it possible to enable the compatibility between two different materials like concrete and timber?**

The compatibility can be enabled first by presenting all the properties and the main issues about timber and concrete (as materials, industrialization and construction practices), enabling the possibility to choose which product would better perform for each specific problem. Second, a more direct answer has been given with the attempt to standardize the product specifications and sizes, according to the concept of modularity and ergonomics.

• **How to increase the use of a “new” material like timber within the construction market?**

The answer to this question would be to provide a simple designing model that is handy for ordinary designers and engineers, and architecturally appealing at the same time. By employing the present framework, a common and easy way for decision-making and thus for industrialization and construction of a timber-concrete hybrid solution has been provided: this would incentivize the timber construction market itself through a preliminary association with concrete market.

Moreover, the framework proposed in this study allows to increase the awareness about the general factors to be evaluated, and to undertake a gradual adoption of new materials and techniques, by highlighting their similarities and compatibilities with the old ones. It is also possible to notice that the key points underlying the whole timber-concrete hybrid problem are standardization and modularity; these concepts can be considered as a bridge for the building companies to move towards a quality-oriented production. The timber-concrete hybrid can be considered a solution for the short middle-future, a starting point to increase the market of wood construction and, perhaps, give the possibility to the concrete industry to softly adapt itself to a new construction market.

5.2. Recommendations

After the overview of timber-concrete hybrid solutions, which can be regarded as a means to increase the awareness on the possibilities to expand the construction market by adopting “new” materials and techniques, and as an invitation for the industry to switch from concrete-only constructions towards timber
constructions, further studies need to be carried out with an applicative intent: there is necessity of mathematical tools, mock-ups and experiments leading to results of general validity, construction practices and norms on timber provided by standardising authorities. More specifically:

- The general frame should be applied in specific contexts and refined according to them, by quantifying both economic and technical factors; thus, some specific case studies need to be carried out;
- Automatic tools for the optimization in construction of timber-concrete hybrids should be developed; these tools should not only consider the technical factors (see e.g. Sills (2014)), but should also match the economic factors;
- Some pilot projects should be undertaken in order to rebuild common buildings and to benchmark concrete-only, timber-only and hybrid equivalent solutions. In these experimental pilot projects, key variables of design, construction and operational life should be identified and monitored;
- To better exploit the timber-concrete synergy, innovative and original hybrid solutions should be explored and studied.
6. References


Annex A: Possibility of standardisation of timber construction products

1. Introduction

The main advantage of the standardisation is the possibility to enable the open system in the construction industry. In both timber and concrete markets, and in general in every construction sector, not using standardised elements implies production of tailored solutions and compliance in the supply chain: this is uneconomical, impractical and increases the risk of error. Besides the saving of time and cost and the higher quality in the design phase, the advantages also relate to the speed of construction, thanks to routine procedures. In particular, prefabrication and standardization lead to reduction of overheads for contractors thanks to (PCI, 2007):

- cheaper housekeeping and lesser levies;
- lower provisions to cover the costs of rectification of defects and potential litigation;
- savings in interest related to shorter construction period and reduction of building defects;
- fewer number of workers and safer construction site conditions;
- better quality of the final product

For the timber construction market, the lack of standardised design guidance represents the main challenge. Currently, technical design data should be obtained from a combination of sources such as manufacturer’s European Technical Approvals, experts’ reports, and handbooks delivered by timber associations (Falk, Dietsch and Schmid, 2016). This lack of consistency and formal agreement in design especially concerns new Engineering Wood Products (EWPs), like CLT, making the designers go back to first and generic principles (e.g. Eurocode 5), not exploiting EWPs’ full benefits. The advantage of standardization in timber market would be to clearly set which are the standard specifications to give for employing the EWPs and to align all the EWPs existing nowadays in a simple and standard product line. This would allow designers and builders to work in an open system and to be decoupled earlier in the supply chain, cutting the dependence with a specific manufacturer (Swedish Wood, 2015).

For the concrete market, the standardization would mean to address the production more onto the precast products. The precast components manufactured in factory, under close supervision, have a higher quality compared to the cast in-situ concrete. Standardization and prefabrication would in addition lead to lower labour costs and waste generation (e.g. by optimizing the use of formwork), allowing savings in learning time on site and higher speed of construction.

The cost of precast components is the sum of (PCI Industry Handbook Committee, 2004):

- Production cost, depending on the type, size and quantity of the precast components (78% to 83%);
- Transportation cost, depending on the distance of transportation and on type and size of the elements (2% to 3%);
- Installation cost, depending on the size and the weight of the elements (15% to 20%).

Generally speaking, the unit cost of the equivalent in-situ components tends to be slightly cheaper than precast components. However, taking into consideration the shorter construction period and other reduced site expenses, the cost of precast components can be competitive (PCI Industry Handbook Committee, 2004).
The standardization of concrete and timber products can proceed together: since the concrete market is already established, whereas timber regulations and producers still need a strong settlement, the timber standards could follow the concrete footprint. Another key point for standardization is the coordination between structural engineers and contractors, fundamental to enable the open system in construction and thus the growth of the timber market. As requirement and aim of the standardization, there is the necessity of buildable projects right from the start of the design process. Precast concrete and standard timber products can be identified as a mean to obtain buildable designs and improve site productivity.

2. Main Concrete and Timber Producers

The process of standardisation needs to look at the current main producers in the market of both concrete and timber construction (Table A-1), focusing on Europe and America (China is here excluded, despite the presence of very big cement companies).

Table A-1. Main Concrete and Timber Producers.

<table>
<thead>
<tr>
<th>Main Concrete Producers</th>
<th>Main Construction Wood Producers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lafarge (France)</td>
<td>Massivholz – KLH, Austria</td>
</tr>
<tr>
<td>Holcim (Switzerland)</td>
<td>Binderholz – BBS, Austria</td>
</tr>
<tr>
<td>Heiderlberg Cement (Germany)</td>
<td>Stora Enso – CLT, Finland</td>
</tr>
<tr>
<td>Cemex (Mexico)</td>
<td>Finnforest – LENO, Finland</td>
</tr>
<tr>
<td>Italcementi (Italy)</td>
<td>Mayr Melnhof - M1 BSP, Austria</td>
</tr>
<tr>
<td>Votorantim (Brazil)</td>
<td>HMS Bausysteme - HMS BSP, Germany</td>
</tr>
<tr>
<td>CRH (Ireland)</td>
<td></td>
</tr>
<tr>
<td>Buzzi (Italy)</td>
<td></td>
</tr>
<tr>
<td>Eurocement (Russia)</td>
<td></td>
</tr>
</tbody>
</table>

*a* http://www.globalcement.com/magazine/articles/741-top-20-global-cement-companies

*b* (Gandelli, 2011)

*c* although not within the main timber producers in Europe, “Martinsons” should be mentioned for the Swedish market

3. Engineering Wood Products

A problem with the Engineering Wood Products (EWPs) is firstly represented by the lack of standardization in specifying structural properties and dimensions of the elements. Here the main EWPs are listed, highlighting their geometrical aspects (Swedish Wood, 2015):

- **Cross Laminated Timber (CLT):** made of uneven number of layers (3, 5, 7) stuck crosswise. The size of CLT panels depends on the possibilities of the manufacturer. The maximum dimensions are: 500 mm for thickness, 3.000 mm for width and 24.000 mm for length;
- **Laminated veneer lumber (LVL):** made of wood veneer sheets (2-4 mm) stuck together to form structural panels (20-90 mm thick) with maximum size 3.000 × 24.000 mm;
- **Plywood:** made in the same manner as LVL, but with the veneers (2-4 mm) laid up perpendicular to each other. Typical sizes are 1.200 × 2.400 mm or 1.220 × 2.440 mm and 12-24 mm thick;
- **Engineered wood products based on strands, chips, or fibres:** manufactured from thin sliced wood strands. The most commonly used product is the Oriented Strand Board (OSB), which can be found in the form of panels with a size of 1.200 × 2.400 mm and 6-25 mm thick. OSB can also be manufactured in larger panels with width up to 3 m, length up to 25 m, and thickness up to 75 mm.
There is a large variation in the panels features and structural performance across the different manufacturers. Since CLT is one of the newest EWP s, and therefore the one that lacks standard specifications the most, the discussion will be mainly focused on it, keeping in mind that the same considerations apply for the other EWP s as well. The main characteristics to consider for EWP s production are:

- thickness of the lamellas
- production process (for CLT: with or without cross joint, one or two phases)
- type of glue
- type of rough wood
- number of layers

It should be noticed that all this information comes from the European Technical Approvals (ETAs), created thanks to the collaboration among manufacturers and certification bodies, given the lack of a standard European Normative. The main information provided by the most significant and recent ETAs have been listed in Table A-2 (Brandner, 2014):

- dimensions: length/width/thickness (l/w/t) [m]
- timber species and strength class
- max gap with [mm]
- number of layers
- presence of edge bonding
- adhesive system
- surface pressing
- EPC test procedures for CLT

Table A-2. Main characteristics of CLT products according to different European Technical Approvals (ETA) (Brandner, 2014)

<table>
<thead>
<tr>
<th>Technical approval</th>
<th>Dimension CLT l [m] / w [m] / t [mm] further information</th>
<th>Dimension BM (SP) 1) w [mm] / t [mm] further information</th>
<th>Timber species 2) strength class</th>
<th>Max gap width [mm]</th>
<th>Single-layer panels (Y/N/possible)</th>
<th>Edge bonding (Y/N/possible)</th>
<th>Adhesive system 3)</th>
<th>Surface pressing</th>
<th>FPC test procedures for CLT 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>large elements ≤22/≤3.5/≤51≤215 system format ≤5/≤1.25(24)/54≤350</td>
<td>large elements 100≥200/17≥43 system format 80≥250/18≥45 TL w/t≥4</td>
<td>SW C16/C24</td>
<td>4</td>
<td>Y</td>
<td>Y/N</td>
<td>EN301</td>
<td></td>
<td>RS or Sh; D; FJ; LFJ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MUF 1K-PUR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[2]</td>
<td>≤20/≤4/45≤280 3≤7 layers</td>
<td>40≥300/15≥40 TL w/t≥4</td>
<td>SW ≥C16</td>
<td>2(4)</td>
<td>pos.</td>
<td>pos.</td>
<td>EN301</td>
<td>vacuum 80≥90 kPa</td>
<td>RS or Sh; D; FJ</td>
</tr>
</tbody>
</table>

A - 3
<table>
<thead>
<tr>
<th>Technical approval</th>
<th>Dimension CLT [m / m / t]</th>
<th>further information</th>
<th>Dimension BM (SP) [m / m / t]</th>
<th>further information</th>
<th>Timber species</th>
<th>strength class</th>
<th>Max gap width [mm]</th>
<th>Single-layer panels (Y/N/possible)</th>
<th>Edge bonding (Y/N/possible)</th>
<th>Adhesive system</th>
<th>Surface pressing</th>
<th>FPC test procedures for CLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>≤16.5/≤3/42÷500 3÷27 layers</td>
<td>40÷300/14÷45 TL w/tz4 solid wood panels (TL) 250÷1,600/-</td>
<td>SW ≥C16</td>
<td>2(4) pos.</td>
<td>pos.</td>
<td>pos.</td>
<td>TLY</td>
<td>EN301</td>
<td>SP: EPI 1K-PUR</td>
<td>-</td>
<td>RS; DL, D or BS; FJ</td>
<td></td>
</tr>
<tr>
<td>[4]</td>
<td>≤30/≤4.8/≤300 ≥3 layers</td>
<td>80÷220/10÷33 TL w/tz4</td>
<td>SW ≥C16</td>
<td>6</td>
<td>N</td>
<td>-</td>
<td>EN301</td>
<td>-</td>
<td>RS; FJ; DL (D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[5]</td>
<td>≤30/≤4.8/30÷300 ≥3 layers</td>
<td>80÷220/10÷33 TL w/tz4</td>
<td>SW ≥C16</td>
<td>6</td>
<td>N</td>
<td>N</td>
<td>EN301</td>
<td>EN15425,</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[6]</td>
<td>≤18/≤3/36÷280 3÷7 layers</td>
<td>70÷220/12÷40 TL w/tz4</td>
<td>SW ≥C16</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>EN301</td>
<td>MUF</td>
<td>-</td>
<td>RS or Sh; D; FJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[7]</td>
<td>≤5/≤1.25(24)/60÷350 ≥3 layers</td>
<td>80÷250/18÷45 TL w/tz4</td>
<td>SW C16/C24</td>
<td>TL 2 LL 0</td>
<td>Y</td>
<td>LL Y</td>
<td>EN301</td>
<td>SP: MUF</td>
<td>1K-PUR</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[8]</td>
<td>≤18/≤3.5/60÷400 3÷11 layers</td>
<td>LL 80÷260/15÷45 TL</td>
<td>80÷260/15÷40 TL w/tz4 solid wood panels -15÷45</td>
<td>S,P,F,L</td>
<td>LL 3 TL 6</td>
<td>Y/N</td>
<td>N</td>
<td>EN301</td>
<td>MUF</td>
<td>pneumatic 0.5÷0.8 Mpa</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>[9]</td>
<td>≤16.5/≤3/57÷500 3÷27 layers</td>
<td>80÷240/10÷40 TL w/tz4</td>
<td>S ≥C16</td>
<td>3(6)</td>
<td>-</td>
<td>-</td>
<td>EN301</td>
<td>1K-PUR</td>
<td>-</td>
<td>RS; D; FJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10]</td>
<td>≤18/≤3/60÷300 3÷9 layers</td>
<td>LL 80÷240/20÷80 TL</td>
<td>80÷240/20÷40 TL w/tz4</td>
<td>S,P,F,L, D ≥C16</td>
<td>LL 3 TL 6</td>
<td>-</td>
<td>-</td>
<td>EN301</td>
<td>EN15425</td>
<td>hydraulic 0.6 Mpa</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>[11]</td>
<td>≤15.5/≤3.45/27÷210 3÷7 layers</td>
<td>60÷300/9÷30 TL w/tz4</td>
<td>S,F C16÷C3 0</td>
<td>2(4) -</td>
<td>LL pos.</td>
<td>EN301</td>
<td>-</td>
<td>D or BS; FJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>≤20/≤4/57÷280 3 or 5 layers</td>
<td>80÷200/19÷45 TL w/tz4</td>
<td>S or sim. ≥C16</td>
<td>3 pos.</td>
<td>LL pos.</td>
<td>EN301</td>
<td>MUF</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) BM base material; SP single-layer panel; TL transverse layers; LL longitudinal layers; TI top layer; CI core layers; w width; t thickness
2) SW softwood species; S Norway spruce; P Scots pine; F White fir; L European larch; D Douglas fir; sim. similar timber species strength class according to EN 338 [8] (or EN 1194 [28], prEN 14080 [13])
data of technical approvals complemented by manufacture’s data (product leaflet, reports, etc.); adhesives according EN 301 [26] only of type I
4) RS rolling shear of CLT; BS block shear CLT; FJ finger joint; DL delamination CLT; D delamination (dispartment at glue line) according to DIN 53255 [54]; B(t) transverse third-point bending; Sh (rolling) shear test
5) The European technical approvals are listed at the end of this document

4. Structural parameters

As seen in the section above, many differences relate to the method of production. However, one might think that what is important for the construction firms is the final product, not how it is processed; therefore, differences in process may endure as long as the final product complies to a set of specifications related to structural properties and dimensions. Despite this consideration, differences related to the method of production often affect the properties of the final product, as it is possible to note in Table A-3, which shows how CLT panels obtained by using wood of strength class C24 have variations in each strength property, depending on the producer.

Table A-3. Performance properties from main CLT manufacturers for panels made with C24 boards (Falk, Dietsch and Schmid, 2016)

<table>
<thead>
<tr>
<th>MANUFACTURER</th>
<th>Binderholz</th>
<th>KLH</th>
<th>MMK</th>
<th>Stora Enso</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>480</td>
<td>550</td>
<td>480</td>
<td>500</td>
</tr>
<tr>
<td>Modulus of Elasticity Eₐ,mean</td>
<td>11000</td>
<td>12000</td>
<td>11600</td>
<td>12500</td>
</tr>
<tr>
<td>E₀,5</td>
<td>7400</td>
<td>9500</td>
<td>7772</td>
<td>7400</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>Gₐ,mean</td>
<td>690</td>
<td>690</td>
<td>650</td>
</tr>
<tr>
<td>Actions perpendicular to the panel (N/mm²)</td>
<td>370</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending Strength fₑ,mean</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>Tensile Strength fₑ,₀,1a</td>
<td>0.4</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Compressive Strength fₑ,₀,2a</td>
<td>2.5</td>
<td>2.7</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Shear Strength fₓ,₀</td>
<td>2.5</td>
<td>2.7</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>Actions in plane of the panel (N/mm²)</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity Eₐ,mean</td>
<td>11000</td>
<td>12000</td>
<td>11600</td>
<td>12500</td>
</tr>
<tr>
<td>E₀,5</td>
<td>7400</td>
<td>9500</td>
<td>7772</td>
<td>7400</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>Gₐ,mean</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Bending Strength fₑ,mean</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Tensile Strength fₑ,₀,1a</td>
<td>14</td>
<td>16.5</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Compressive Strength fₑ,₀,2a</td>
<td>21</td>
<td>24</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Shear Strength fₓ,₀</td>
<td>2.5</td>
<td>5.2</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Tables for EWPs’ structural design should show the strength properties listed in Table A-4 and Table A-5. This kind of table applies to solid timber, glulam, LVL, plywood, OSB, Particleboards, fibreboards, and CLT (which is the one that especially lack of defined standards); thus, it applies to unidirectional and bidirectional loadbearing products.
The strength properties are affected by the moisture content of the wooden fibres, which varies with the moisture change in the external environment. To take into account this variation of the strength properties, some reduction coefficients have been introduced depending on certain service classes. Load bearing boards should be designed for use in dry conditions or use in humid conditions.

5. Dimensions

Variation in dimensions of the panels consist of:
- variation of the overall thicknesses among panels produced by different CLT manufacturers (Table A-6);
- variation of the lamellas thicknesses (thus, variation of the inner composition and the structural properties) among panels with the same overall panel thickness, but produced by different CLT manufacturers (Figure A-1).
There have been attempts by some CLT manufacturers to standardize overall panel thickness, which is helpful for engineers to design in easier and more independent way, without the need of a continuous and time-consuming feedback from the manufacturer (Falk, Dietsch and Schmid, 2016). The matching thickness for the main producers are then 60, 90, 100, 120, 140, 160, 180, 200 mm. It is possible to deduce that a 20 mm could be the standard unit size for the thickness of lamellas, and the overall thickness of the panel would be multiples of 20 mm.

**Table A-6.** (left) Panel thicknesses from main CLT manufacturers

**Figure A-1.** (right) Cross sections of two CLT panels with the same overall thickness from different manufacturers. (Falk, Dietsch and Schmid, 2016)

Besides the thickness, there are differences in the width and length among the various producers (Figure A-2). Nowadays, the maximum dimensions of EWPs are: 18-24 m in length (in exceptional cases even 30 m); 4-4.8 m in width (typical panel widths are 1.2 m 2.4 m 3 m); 0.3-0.4 m in thickness (even 0.5 m is possible) (Gandelli, 2011; Brandner, 2014).

**Figure A-2.** Typical CLT panel sizes of different manufacturers (Gandelli, 2011)

When speaking of dimensions, the modular construction system assumes great importance: entire volumetric boxes consisting of walls, floor, and ceiling, as well as inner claddings and all services, are assembled in a factory and delivered to the building site for erection. Limitations in span is about 4 m, due to transportation. The modules are assembled on top of each other, by means of a male-female connection. In Figure A-3 are shown the typical dimensions of a prefabricated modulus (Swedish Wood, 2015).

**Figure A-3.** typical dimensions of a prefabricated modulus (Swedish Wood, 2015).
In order to determine the suitable standard dimensions of EWPs, a number of issues are to be considered, like transportation limits, storage and erection in construction site, modular architectural design, and benchmarking with existing concrete prefabricated products.

5.1. Transportation limitations

Transportation limitations (as highway regulations, weight and dimensions allowed for type of vehicles, and construction site space) should be always considered before undertaking the design of prefabricated buildings. Transportation limits vary depending on the jurisdictions areas, even if international transportation agree on some common standards. In Table A-7 are listed the most common items’ sizes allowed according to the road vehicles standards in North America and Europe, taken as main reference points (see also Figure A-4).

![Figure A-4. a) Standard transport with delivery standing upright and delivery lying flat; b) special transport (Bausysteme Binderholz GmbH, 2016)](image)

**Table A-7. Dimension allowed for prefabricated product to be transported in most popular vehicles.**

<table>
<thead>
<tr>
<th>Transportation area and type of vehicle</th>
<th>Length [m]</th>
<th>Width [m]</th>
<th>Heigh [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.A. (semi-trailer)(^{a})</td>
<td>16,15</td>
<td>2,50</td>
<td>4,11</td>
</tr>
<tr>
<td>U.S.A. (dropdeck semi-trailer)(^{a})</td>
<td>12,80</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>USA (Double Dropdeck semi-trailer)(^{a})</td>
<td>9</td>
<td></td>
<td>3,56</td>
</tr>
<tr>
<td>Europe - Standard-planenwagen(^{b})</td>
<td>13,40</td>
<td>2,55</td>
<td>3</td>
</tr>
<tr>
<td>Europe - Special transport (teleskop-satteauflieger)(^{b})</td>
<td>18-21</td>
<td></td>
<td>3-3,50</td>
</tr>
</tbody>
</table>

\(^{a}\) (FPInnovations, 2011)  
\(^{b}\) (Bausysteme Binderholz GmbH, 2016)

5.2. Modular planning

Modularity is the key to succeed when designing with the purpose to obtain flexibility (and then standardization and open system). When dealing with prefabricated components - especially if made of
different materials like concrete and wood in a hybrid construction solution - modularity allows to reach the coordination needed for the combination and the interaction between them.

The modular coordination starts in the architectural design stage. The basis for modular planning is to set out a suitable layout design with uniform pattern: the modular distance between the grid lines shall, as far as possible, be equal. The basic modular grid will define the major planning line-up where the main structural components (such as columns, beams and floor slabs) are being placed and co-ordinated, avoiding strictly defined arrangements. Thereafter, the architect must decide where to place the architectural components; for example, the wall panels may be placed on the outer part of the grid or in-line with the grid (Figure A-5).

The overall design layouts could be an assembly of many similar sub-modules or clusters, which could be repeated, turned, or mirrored (Building and Construction Authority (BCA), 2010)

Figure A-5. Modular lay-out. Horizontal and Vertical controlling dimension (Building and Construction Authority (BCA), 2010)
The most common modular reference system of a basic planning grid is set to 300 mm or 3M (where M = 100 mm). In general, 3M is recommended for the horizontal multi-module and 0,5M for the vertical multi-module. Table A-8 presents the recommended modular dimensions that will provide sufficient flexibility in the design of private residential buildings. It is possible to introduce sub-modular increments of 0,25M or 0,5M. In this perspective, the typical size of the rooms in common housing should also be considered, in order to choose the most suitable modular units (Table A-9).

**Table A-8. Recommended dimensions in modular planning (Building and Construction Authority (BCA), 2010)**

<table>
<thead>
<tr>
<th>Basic module M (M = 100 mm)</th>
<th>Structural grid 12M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal multi-module 3M</td>
<td>Vertical multi-module 0,5M</td>
</tr>
<tr>
<td>Column size 0,5M</td>
<td>Beam size 0,5M</td>
</tr>
<tr>
<td>Floor thickness 0,5M</td>
<td>Door width 3M</td>
</tr>
<tr>
<td>Door height 1M</td>
<td>Window width 3M</td>
</tr>
<tr>
<td></td>
<td>Window height 1M</td>
</tr>
</tbody>
</table>

**Table A-9. Typical room dimensions**

<table>
<thead>
<tr>
<th>Room</th>
<th>Dimensions [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen</td>
<td>2,40-2,80 x 3,60-4,00</td>
</tr>
<tr>
<td>Living room</td>
<td>3,90-3,20 x 2,40-2,70</td>
</tr>
<tr>
<td>Corridor</td>
<td>1,20</td>
</tr>
<tr>
<td>Bed room</td>
<td>3,60 x 4,00</td>
</tr>
<tr>
<td>Small bed room</td>
<td>2,30-2,70 x 4,00</td>
</tr>
<tr>
<td>Staircases</td>
<td>stairs 2,40-2,70</td>
</tr>
<tr>
<td></td>
<td>landing 1,35-1,50</td>
</tr>
<tr>
<td></td>
<td>elevator 2,10 x 2,00</td>
</tr>
</tbody>
</table>

5.3. Modular coordination in precast concrete

Concrete market already has a set of prefabricated elements, but their use is often limited by the common perception that precast concrete lacks flexibility. Nevertheless, by using more industry standardized components (e.g. staircases, internal and exterior wall panels, etc.) the cost for the precast components themselves, and then of the building, will be reduced; for example, the traditional method of applying exterior finishes on site can be avoided by using the pre-finished elements (PCI Industry Handbook Committee, 2004). The standardisation of the EWPs’ dimensions should look at the precast concrete market to enable compatibility and interchangeability with precast concrete elements, and therefore enabling an easier use of timber in construction of buildings.

A first difference in prefabrication of the timber and concrete elements is the use of the mould. Producers often adopt a master mould concept to optimise their production. The concept is to design the largest possible panel mould for a particular facade panel, whereby several variations from the same mould can be produced by varying mould component accessories (PCI Industry Handbook Committee, 2004). There are no specific restrictions on the shape of precast elements; however, it is necessary to recognize the tolerances. This is a good example of how to optimise the production of standardised elements, by using the concept of modularity with multiple and submultiples dimensions. Several construction systems within the precast concrete market are listed below (Singapore Institute of Architects, 1999); the focus is on the dimensions of the elements used in each case, so that matching and guidelines can be found for the timber products.
1. Precast frame and skeletal system

- **Plinth**: Prefabricated plinths are placed on a cast in situ base. Pillars are inserted in the hole of the plinth and fixed by soaking them with a sealing jet of shrinkage concrete. The maximum sizes of the plinths are conditioned by the transport: thus, one of the sides in the plant must not exceed 250 cm. Common dimensions are 230 x 230 x 145 (h) cm or 200 x 200 x 120 (h) cm (Tre Colli, 2016)

- **Columns**: Columns can be produced with a square or rectangular cross section with 30 to 100 cm side according to multiple of 5 cm. One segment can reach 15 m of height and several segments can be stacked one upon another to achieve greater heights. It is possible to provide the pillars with appropriate supporting shelves for intermediate floors, on each side of the column and in variable number and position (Tre Colli, 2016)

- **Beams**: The cross section of the beams can be rectangular, reverse T shaped, or L shaped, with dimensions that usually vary according to multiples of 10 cm. The length can be set in freely.

2. Precast floor

- **Hollow core floor**: precast reinforced or pre-stressed concrete planks (edges and lengths are maximum 9 m and 12 m respectively); some of these are used as internal wall panels.

- **Ribbed soffit floor**: can be found in the shape of single-T or double-T. They are a combined beam and slab structure (maximum span about 22 m); they have excellent stability and load-bearing capacities.

- **Composite half-slab floor**: thin precast slabs combined with in-situ reinforced concrete topping to achieve a robust composite floor (0.6 to 2.4m wide; 40-100 mm thick).

- **Composite hollow core and ribbed soffit floor**: concrete topping (50-100mm); thicker topping allows pipes and conduits to be concealed within the topping.

3. Precast load bearing wall and facade system

Precast load bearing wall and facade system consist of cross-walls, walls in shafts and cores, and load-bearing facades. The same specifications of the floor slabs apply here. Typical precast lightweight concrete panel systems are:

- **Solid panel**: length 2.4-3.6 m, width 600 mm; thickness 75 mm; weight 160-240 kg

- **Hollow core panel**: length up to 5.85 m; width 600 mm; thickness 80 mm or 100 mm; weight 68 kg/m2 for 100 mm thick panel

Some of the precast elements listed above are presented in Figure A-6 with some specifications in Table A-10.
Figure A-6. (above) Table A-10. (below) Typical precast concrete products with relates dimensions.

<table>
<thead>
<tr>
<th>Foundation Piles</th>
<th>Cross-sections 15x15 - 45x45 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Beams b) Columns</td>
<td>With/heights up to 50 cm in variable widths up to 40 cm</td>
</tr>
<tr>
<td>c) Lintels</td>
<td>Depths 7 to 15 cm</td>
</tr>
<tr>
<td></td>
<td>widths 10 to 18 cm</td>
</tr>
<tr>
<td>d) Hollow core floor slabs</td>
<td>With depths 8 to 50 cm</td>
</tr>
<tr>
<td></td>
<td>widths of 30, 40, 60, 120, 150 and 240 cm</td>
</tr>
<tr>
<td>e) Wall- Panels</td>
<td>solid produced or as sandwich on tilt-tables, up to 30 cm in depth; Hollow core produced on casting beds cut to 2-6 m length with 8 to 20 cm depth and in variable width of 30, 40, 60, 120, 150, 240 cm</td>
</tr>
<tr>
<td>f), g) Roof-Elements</td>
<td>f) TT-Slabs: width up to 240 cm; height 70 cm</td>
</tr>
<tr>
<td></td>
<td>g) V-Elements: width up to 120 cm; height 60 cm</td>
</tr>
</tbody>
</table>
4. Precast cell system

Precast cells consist of precast bathrooms, shelters, lift cores, and staircase cores. Precast cell system has large in-plane stiffness and strength; the disadvantage is the limitation in size because of its (PCI Industry Handbook Committee, 2004).

- **Precast prefabricated bathrooms**: are often used in housing, hotels and hospitals projects for ease of handing over and maintenance, in the perspective of more buildable and zero-defect building. Gaps for tolerance are provided between the units and there are supporting structural slab or walls for ease of installation, concealed piping, wiring, and maintenance. Precast bathrooms accelerate the construction and the delivering of the building, since it is possible to avoid the finishing work, which is the most difficult task in a residential development.

- **Precast staircase**: it is possible to obtain whatever shape of staircase by employing precast concrete. The staircase can be prefabricated together with landing as a complete unit or without, in which case the landing may be prefabricated separately or cast in-situ with the structural member.

- **Precast shelter**: (Figure A-7) Precast shelter can be Household Shelters (HS) or Storey Shelter (SS). Shelters are modular (Table A-11) and complete with fixtures: the electrical installation and communication system in the shelter shall include lighting, power, telephone, radio and television outlets. There are different types of shelters:
  - *Single precast unit*: usually about 20 tonnes; too heavy to be lifted by normal site equipment
  - *C Shape wall units*
  - *Semi-precast unit*
  - *Precast door frame panel with ventilation sleeve*
  - *Precast concrete cell with hollow walls*: can be handled by lifting equipment on site.

**Table A-11. Standardised shelter; recommended internal dimension (Singapore Institute of Architects, 1999)**

<table>
<thead>
<tr>
<th>Gross Floor Area (GFA) Of Dwelling Unit</th>
<th>Minimum Internal Clear Floor Area Of HS</th>
<th>Nominal Occupancy Of HS (No. Of Person)</th>
<th>Recommended Internal Dimensions Of HS (W)x(L)x(H)</th>
<th>Thickness Of Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFA ≤ 45 m²</td>
<td>2.0 m²</td>
<td>2</td>
<td>1.2 x 1.8 x 3.0</td>
<td>275 mm</td>
</tr>
<tr>
<td>75 m² ≥ GFA &gt; 45 m²</td>
<td>2.4 m²</td>
<td>3</td>
<td>1.2 x 2.1 x 3.0</td>
<td>275 mm</td>
</tr>
<tr>
<td>140 m² ≥ GFA &gt; 75 m²</td>
<td>3.2 m²</td>
<td>4</td>
<td>1.5 x 2.4 x 3.0</td>
<td>275 mm</td>
</tr>
<tr>
<td>GFA &gt; 140m²</td>
<td>4.0 m²</td>
<td>5</td>
<td>1.5 x 2.4 x 3.0</td>
<td>300 mm</td>
</tr>
</tbody>
</table>

**Figure A-7. Example of precast shelter with typical dimensions (Singapore Institute of Architects, 1999)**
As for the timber construction products, transportation regulations shall be considered when designing and building with precast concrete elements. In general, maximum products’ size allowed on the vehicle are 335 cm height and 240 cm width. Here, special attention shall be payed when the precast concrete unit is loaded onto the vehicle: it shall be attached firmly to the supporting members and fastened with a position locking device, in order to avoid undesirable stresses to the precast elements, due to flexing of truck (Singapore Institute of Architects, 1999). Moreover, the high weight of the precast elements represents a stricter restriction compared to timber elements.

6. Conclusions

By considering all the factors named above, which influence the dimensions of construction products, a suggestion of standard sizes is proposed as in Table A-12.

Table A-12. Resume of suggested standard dimensions for EWPs products.

<table>
<thead>
<tr>
<th>Factors to consider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current production of main EWP manufacturers</td>
</tr>
<tr>
<td>Modular coordination guidelines</td>
</tr>
<tr>
<td>Typical architectural room sizes</td>
</tr>
<tr>
<td>Transportation limitations</td>
</tr>
<tr>
<td>Compatibility with prefabricated concrete elements</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions suggested for EWPs standardisation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickness</strong>: The matching thickness among the main manufacturers are: 60, 90, 100, 120, 140, 160, 180, 200 mm. It is possible to deduce that a 20 mm could be the standard size for the thickness of lamellas; thus, the overall thickness of the panel can be multiples of 20 mm. Typical thickness of the floor reaches 30-40 cm (but even 50 cm in some cases)</td>
</tr>
<tr>
<td><strong>Width</strong>: The suggested standard width mostly derives by comparing and matching the current widths in EWPs market. Nowadays, typical panel widths are 1.2 m, 2.4 m, 3 m; maximum width reaches 4-4.8 m. The match of widths should be found also for concrete panels: floor slabs like double T and hollow slabs usually are 1.20 or 2.40 m large; the same apply for walls. Therefore, for standard widths multiple of 0.6 m can be applied (also in accordance with the horizontal modular coordination of 3M). By considering typical transportation regulations, the maximum width is 2,40 if panel are stored horizontally in the vehicle, 3 m if stored vertically.</td>
</tr>
<tr>
<td><strong>Length</strong>: Length is set quite freely, although for the horizontal coordination it is suggested to respect the 3M modularity (30 cm) and for the vertical coordination it is suggested to respect the 0.5M (5 cm) coordination (e.g. concrete columns have shelter with a reason of 5 cm). The maximum length is limited by transportation: usually 13,50 m, up to 21 m for special transportation.</td>
</tr>
</tbody>
</table>

7. References


**European technical approvals**

[0] EN 13986:2002-06, “Wood-based panels for use in construction – Characteristics, evaluation of conformity and marking”


[5] ETA-10/0241 “LenoTec – Solid wood slab elements to be used as structural elements in buildings”, Finnforest Merk GmbH, Deutsches Institut für Bautechnik (DIBt), 2010, valid until 12.08.2015

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Annex B: Material properties and construction products

1. Introduction

There could be many economic and technical reasons to choose a hybrid building solution; however, the main intent is to exploit the properties and the industrialization of the materials, considering both technical and economic aspects. In this annex, the main properties of both concrete and wood, and the related construction products are presented, so that the designer can choose wisely which product to use and for which purpose.

2. Timber

2.1. Material properties

The main advantage of the timber is that it can provide good loadbearing performance at low weight. However, the strength and the stiffness are different depending on the direction, parallel ($\sigma_0$ or $\sigma_{//}$) or perpendicular ($\sigma_{90}$, or $\sigma_{\perp}$) to the fibre direction. For the cross section, the difference between R and T direction is often disregarded. Thus, the number of variables for the strength can be reduced to six: $E_{//}$, $E_{\perp}$, $G_{//}$, $G_{\perp}$, $\nu_{//}$, $\nu_{\perp}$ (Figure B-1). Below are listed the main strength characteristics (Swedish Wood, 2015)

- **Weight**: is very low compared to many other construction materials: the density $\rho_{12}$ (at 12% moisture content) is about 300-600 kg/m³.

- **Tension parallel to the fibre direction** ($f_t$) is very high; the failure stress is of the magnitude of 100 MPa; the failure is often very brittle. The stiffness is also high. (Figure B-2 a)

- **Tension perpendicular to the fibre direction**: the strength of wood loaded perpendicular ($f_{t,90}$) to the fibre direction is very low, in most cases 0.5 MPa (if the wood is loaded in tension perpendicular to the grain the forces to pull apart the fibres or break the fibres are much lower). The stiffness is much lower in this direction. (Figure B-2 b)

- **Compression parallel to the fibre direction**: is quite good ($f_c$ is around 80 MPa) and can withstand high loads (but lower than tension parallel to the fibre). The fibres can be thought as tubes that are very stable when loaded axially. When the load is too high, a plasticising behaviour starts: some fibres will start to buckle and to be driven into the other fibres, reducing the possibility to take higher load. Typical values for $\varepsilon_c$ are 0.8-1.2% with an ultimate strain level $\varepsilon_u=3\varepsilon_c$. (Figure B-2 c)

- **Compression perpendicular to the fibre direction**: is low ($f_{c90}$ around 3-5 MPa): in compression perpendicular to the fibre direction, the tube-shaped wood cells will be crushed. The stiffness is also low. (Figure B-2 d)

- **Loading at an angle $\alpha$ to the grain direction**: If the material is loaded at an angle between perpendicular to grain and parallel to grain, the strength is somewhere between the extreme cases showed above. (Figure B-2 e)

- **Shear strength**: is higher in planes parallel to the fibre direction (between 5 and 8 MPa); in timber structures, shear in the $\tau_{\parallel}$ and $\tau_{\perp}$ direction are the most common. The shear strength perpendicular to the fibre direction $\tau_{T\parallel}$ (rolling shear) is often around 3-4 MPa; it is not so common in normal square beams, but must be considered in some EWPs as glulam I-beams or CLT (Figure B-3).

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1 (Swedish Wood, 2015)
The strength properties might be altered over time (Swedish Wood, 2015):

- **Influence of moisture**: The mechanical properties are affected by the change in moisture content in different way, depending on the direction: the tension strength is almost unaffected, whereas the compression strength is very much affected in both parallel and perpendicular direction to the fibres (approximate 5% for 1% change in moisture content). Then there are, from the most affected to the lowest affected: bending strength parallel to the fibre direction (4%); tension parallel and perpendicular to the fibre direction (2,5 and 2% respectively); shear strength parallel to the fibre direction (3%). All these changes are considered into the structural design by using a coefficient of reduction associated to serviceability class.

- **Influence of time**: The bending strength decreases with the loading time increasing, i.e. duration of load (DOL). This relationship seems to be valid in all loading modes but is especially important in bending strength.

- **Long-term deformations**: Constant loads will lead to increasing deformation with time: this effect is called creep. When the load is removed most of the deformation will be recovered. The deformations are different depending on to the absorption and desorption cycle (Figure B-4).
2.2. Durability

The wood deterioration can be caused by biotic agents (biodeterioration) as fungi, bacteria, and insects, or can be caused by abiotic agents like weathering (e.g. photochemical and hydro-thermal alterations), fire, chemicals, and mechanical agents (e.g. loss of strength when stressed under load for long periods of time, abrasive actions from sand and water).

The main concern is to prevent the growth of microorganisms, and thus to avoid the combination of their favourable condition to grow: moisture should be taken under 30% and it should be avoided to provide nutrients, heat, and oxygen (the optimal conditions for the microorganisms’ growth are moisture about 40-80% and temperature about 25-32°C). Moreover, wood can be attacked by hyphae-growing decay fungi, causing rot and having loss of weight as main consequence. Also, wood can be attacked by mould. About thermal degradation, it should be considered that the wood does not burn instantaneously and loses its strength after a while. In fact, before reaching the wet wood, fire attacks an initial surface, a volatile zone, a pyrolysis zone, and a char layer.

There are some good design practices capable to assure the protection and the long-term performance of the timber products; wood can be preserved through treatment with toxic chemicals (biocides), through modification (physical and/or chemical), or through physical barriers (e.g. coatings). Referring to this last protection method, it is important to assure that water is kept away from the structure by means of drainage measures that dissipate water and moisture from the facades and the nearby ground; perhaps by installing eaves and canopies or by simply removing bushes and trees from near the façade, since they could prevent a good air circulation and hamper the drainage of the adjacent land.

In conclusion, to ensure the durability of the timber structures, it is important to preserve the coating. Various mechanisms may cause the coating failure: moisture movements leading to wood-coating delamination; poor adhesion between wood substrate and coating; poor penetrability; and UV-degradation of the wood.

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2 Information inferred from lectures of Magnus Wålinder’s course “Building Materials, Advanced Course” at KTH - Stockholm
From a practical point of view, the main causes for wood coating failure outdoor are related to a poor design (e.g. end grain too close to ground) and a not correct painting system.

2.3. Engineering wood products

Glued laminated timber (Glulam)

Glued laminated timber is one of the most known and used EWPs. Glulam beams are made by gluing together several lamellas in the same direction; these beams are not significantly stronger than solid beams of the same size but the variability in strength is lower. The most common failure for a glulam beam subjected to bending is a tensile failure parallel to the grain of the outer lamination (often originating in a knot or a finger-joint). Another type of failure that can occur is the shear failure. High tensile stresses perpendicular to the grain need to be considered, especially in curved beams and beams with holes and notches.

Cross-laminated timber (CLT)

Differently to the glulam, CLT is one of the newest and most promising EWPs. It is made of uneven number of layers of boards stacked crosswise and glued together on their wide faces (sometimes, on the narrow faces as well). Panels are usually fabricated with three (at least) to seven layers or lamellas; the use of uneven number of layers resulting in one main spanning direction. CLT is employed to make load-bearing vertical walls and horizontal floor diaphragms thanks to the bidirectional bearing capacity and capability of locking moisture movements. Single curved elements and 3d box elements are made as well. The thickness of the individual boards is about 10-50 mm, while the width is about 60-240 mm. Panels’ typical widths are 0,6 m and 1,2 m, while typical lengths are about 3 m up to 18 m and thickness is up to 400 mm. These sizes are imposed by transportation limitations. Adhesives usually employed are phenol formaldehyde (PF) and phenol-resorcinol formaldehyde (PRF); nails or screws can also be used instead of adhesive; thus, the properties vary.

Laminated veneer lumber (LVL)

Laminated veneer lumber is made of layers of wood veneers (2-4 mm layers of wood) stuck together using a waterproof structural adhesive to form thick (20-90 mm) structural panels. For normal LVL all the layers are oriented with the same fibre direction. The advantage, as for the glulam, stands in the higher reliability and lower variability achieved through elimination and distribution of defects. For the construction, a parallel-lamination process is used where the grain of each layer of veneer runs in the same direction to achieve uniformity and predictability.

Plywood

It is produced roughly in the same manner as LVL, but with the veneers laid up perpendicular to each other; normally the fibres are oriented in the long direction of the panel. For the structural design, it is important to keep in mind the direction of the forces, which could be in-plane or out-of-plane. The layers with grain direction parallel to the direction of the normal stresses have the highest stiffness and take the major part of the load. The contribution to the load bearing capability of the layers with grain direction perpendicular to the direction of the normal stresses is very small and can be disregarded in practice. Typically, plywood is employed for sheathing, façade panels (if treated), structural stabilization, and interior applications.

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3 (Green and Karsh, 2012; Swedish Wood, 2015)
Engineered wood products based on strands, chips, or fibres

The most common within this kind of EWPs is the Oriented Strand Board (OSB), which is manufactured from thin wood strands sliced and pressed together using adhesive. In the outer layers, the strands are oriented parallel to the long direction of the panel, while in the inner layer the strands are oriented randomly. Typically, it is used as sheathing material in walls or floors, but also for structural purpose as beams, wall diaphragms, roof elements, and - if manufactured in larger panels - as structural panels in the same manner as CLT.

2.4. Design

Nowadays the main reference for the timber structure design in Europe is the Eurocode 5 (EN 1995-1-1), which applies mainly to solid timber and glulam structures, providing (unexhaustive) guidelines for LVL, plywood, OSB, particleboards, and fibreboards. CLT design is dealt in handbooks and technical reports, often referring to the Eurocode. The main issues to be considered are:

- **Beams**: single-tapered; double-tapered; curved and pitched cambered; purely curved
- **Instantaneous and final deflection**: bending and shear deformation; creep influence
- **Composite beams, stressed skin panels (SSP)**: possible failure locations; transformed of fictitious cross-sections; shear failure along the glue-line.
- **Design of cross-sections subjected to combined stresses**: compression stresses at an angle to the grain; combined bending and axial compression
- **Stability of members**: columns subjected to either compression or combined compression and bending; beams subjected to either bending or combined bending and compression

The following checks are to be carried out:

- Tension parallel to the grain
- Tension perpendicular to the grain
- Compression parallel to the grain
- Compression perpendicular to the grain
- Bending
- Shear
- Serviceability limit states (e.g. deflection and vibration often dominate design)

**Strength properties**

For the design of timber structures, a set of mechanical properties is needed as presented in Table B-1 and Table B-2.
The strength properties are affected by the moisture content of the wooden fibres, which varies with the moisture change in the external environment. To take into account this variation of the strength properties, some reduction coefficients have been introduced depending on certain service classes. Load bearing boards should be designed for use in dry conditions or use in humid conditions.

2.4.1. Design of CLT structures

Special focus is needed for the CLT structures, which lack of regulations and guidelines regarding the structural design. Structural design and serviceability for floor and roof mainly regards: in plane and out of plane bending and shear strength and stiffness; short and long-term behaviour (instantaneous deflection, long term strength for permanent loading, long term deflection); vibration performance of floors; and compression perpendicular to grain strength. For the design of wall elements, the load bearing capacity is critical, but also in-plane and out-of-plane shear and bending strength need to be verified. Other key design aspects to be considered are fire protection, sound insulation, and durability.
Structural Design\(^5\)

Nowadays the experimental approach is the most commonly employed when designing with CLT: some tests are carried out on full size panels with specific span-to-depth ratio in order to determine the flexural properties. The problem is that every time lay-up, type of materials and manufacturing properties change. An analytical approach (after having been proved with tests) would offer general and less costly alternative to predict strength and stiffness basing on input material properties of laminated boards. No analytical approach has been universally accepted by European CLT manufacturer and designers.

Nowadays, the most common adopted approach for CLT design refer to the mechanically jointed beams theory (in Annex B of Eurocode 5), based on the “effective stiffness” concept and the “connection efficiency factor” for the shear deformation of the perpendicular layer. However, one specific aspect of CLT, as an orthogonal laminar structure in comparison, is the shear flexibility due to rolling shear in the cross layers, which could not be dealt with Euler-Bernoulli beam theory neither with alternative approach like “Composite theory (k-method)” (Blass and Fellmoser), which is used to predict flexural properties without considering the shear deformation. There are some new theories capable to deal with the shear flexibility, like the “Gamma-method”, the “Shear analogy method”, and the “Transverse shear-flexible beam” (Timoshenko). In conclusion, the methods used in Europe focus on flexural stiffness and not on strength because the design is mostly governed by serviceability criteria. However, from the point of view of a standard products development, there is a need to characterize the strength as well, to ensure certain minimum strength of the panel in service. Little information exists on vibration and creep.

Seismic design\(^5\)

Wall panels constitute an effective lateral load resisting system. Good performance is achieved when nails or slender screws are used with steel brackets to connect the walls to the floor beneath, but this solution should be avoided in high seismic areas, as well as diagonally placed long screws to connect wall and floor, because they lead to a lower ductility and brittle failure mechanism. Step joints are used in longer walls to reduce the stiffness and improve deformation capabilities. In general, the platform structural system is less susceptible to develop soft storey mechanism; the non-linear behaviour is localized on the hold-down and bracket connections areas only, whereas the panels of vertical load-carrying element are left intact in place and well connected to floor, enabling all the walls to contribute to the lateral and gravity systems.

The practice today for seismic design in mass timber building, is to calculate the “R” values. All commonly used lateral load resisting systems are assigned an $R_d$ and $R_0$ values in the National Building Code. The higher the ductility of a system, the higher the associated $R$ factors and, as a result, the lower the required seismic design forces. “R” values have yet to be assigned for solid wood panel construction in the building codes and this lead engineers to use practical tests to determine the seismic behaviour.

Main characteristics of CLT structures\(^6\)

- **Connections and Construction:** Connections are very important to enhance strength, stiffness, stability and ductility of the structure. Nowadays, European design procedure only deals with the ductile design modes to determine the lateral load resistance by means of empirical expressions of

\(^{4}\) (Falk, Dietsch and Schmid, 2016)  
\(^{5}\) (FPInnovations, 2011)  
\(^{6}\) (FPInnovations, 2011; Green and Karsh, 2012; Swedish Wood, 2015)
European Yield Model (EYM), treated in Eurocode 5. Brittle failure mode has not been investigated yet.

- **Duration of Load and creep behaviour**: Due to orthogonal arrangement of the layers and the panels mechanically fastened, CLT is more prone to creep than other EWPs.
- **Vibration performance of floor**: CLT structures are subjected to vibration. No established method exists to check the vibration performance; thus, specific tests are carried out for each building case.
- **Fire performance**: CLT has good fire resistance, since it slowly chars at a predictable rate. There are simple but conservative design procedures based on the state of art in Europe (Reduced or effective cross-section method) and North America (CSA 086).
- **Sound insulation**: Sound insulation performance is evaluated on the sound transmission class (STC) and the impact-sound insulation class (IIC). CLT floor and wall assemblies have good acoustic performance (benchmarked to other existing solutions).
- **Building Enclosure design**: The key for CLT durability is to keep it dry. Attention should be payed to control the moisture level during construction by delivering CLT just on time, using temporary roofing system that is moved as the building goes up.

### 2.4.2. Connections

Firstly, an overview about the timber connections is here presented. Distinction is made between carpentry joints and mechanical joints, which can be made of several types of fastener like nails, dowels, bolts, screws, split ring connectors, toothed-plate connectors, and punched metal plate fasteners. The arrangement and sizes of the fasteners and their spacings, edge, and end distances in a connection shall be chosen so that the expected strength and stiffness can be obtained. The failure of the connection includes both crushing of the timber and bending of the fastener. For the determination of the characteristic load-carrying capacity of connections with metal dowel-type fasteners, the contributions of the yield strength, the embedment strength, and the withdrawal strength of the fastener shall be considered. Moreover, group effect of the nails should be considered, which causes row shear, block shear, plug shear, and splitting.

There is a special focus on the CLT connections (Figure B-5), which are important to create the so-called platform construction, that is method of ‘stacked’ construction used in multi-storey timber structures. Floor panels bear on top of the wall panels and subsequent wall panels are then erected on top of the floor panels. The panels are fixed together using a combination of screwed half lap joints and metal brackets. There are three different CLT building structural forms: cross-wall; loadbearing façade/corridors; or hybrid (CLT/steel frame, CLT/glulam frame). CLT connection can be of two types: screws or Proprietary metal brackets / 3-dimensional nail plates (3DNP) (Figure B-6).

![Figure B-5. Typical joints/connections of a CLT platform structure (Falk, Dietsch and Schmid, 2016).](image-url)
• **CLT wall to concrete connections (type A):** CLT wall panels are connected to the concrete foundation using 3DNP. The gap between the bottoms of wall panels and the concrete slab are filled with non-shrink cementitious grout to ensure the structure loading is transferred to foundations as uniformly distributed line loads.

• **CLT wall to CLT floor connections (type B):** The installation and fabrication tolerances of this connections is easier where CLT floor slabs are supported on top of the walls and the next wall is located on top of the slab; moreover, a direct load path is created to the horizontal shear loads between floor slabs and walls. The disadvantage is that in taller buildings, where vertical loads are higher, the compression perpendicular to the grain on the floor slab tends to be a limiting factor. Connection type B can be subdivided into two categories: “slab to wall” (fastening of the floor slabs down to the top of the underneath wall by using structural washer head screws partially threaded providing shear capacity; “wall to slab” (3DNP partially or fully nailed to both wall and floor panels).

• **Half laps and wall junctions (types D & E):** These connections are made to tie all panels next to each other. The floor-to-floor junctions are usually formed with washer head screws installed through the half lap joint; the wall-to-wall junctions are usually formed with washer head screws to simply clamp the panels together, or with 3DNP if a higher load need to be transferred.

• **Roof parapet connections (type C):** The main action that the parapet connection must transfer to the roof slab is the horizontal wind load. There are different approaches to solve the joint: if the parapet height is not significant, small ribbed 3DNP and a screw can be used; for higher parapet, a nail plate can be added in the external face; finally, the parapet (if not high) can be a cantilever member of the wall.

• **Special connections:** Often special connections are required; panels should be provided already in the factory process with a predisposition for the specific connection (bearing detail/connection can be pre-cut in the factory to help installation on site and minimise the number of connectors required). Some examples are: cantilever stair half landings with steel angles (top and bottom) to form a moment connection and fixing of localised steel elements such as lintel beams.

![Figure B-6. a) Structural screws (Eurotec); b) TITAN bracket (Rothoblaas); c) ABR105 bracket (Simpson Strong-Tie)](image-url)

3. **Concrete**

3.1. **Ordinary concrete**

• **Weight:** The density of concrete can vary, but in general it is around 2 400 kg/m³; there are lightweight aggregate concrete (800–2.000 kg/m³), normal weight concrete (2.000-2.600 kg/m³), heavyweight concrete (2.600 kg/m³). There is a distinction in normal weight concrete (C) C12-C120,  

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7 (fédération internationale du béton (fib), 2013)
and lightweight aggregate concrete (LC) LC8-LC80. With increasing compressive strength, the percentage of cement increases and the percentage of water decreases; thus, high strength concrete (HSC) has a higher density compared to normal strength concrete (NSC).

- **Compressive strength**: Concrete has relatively high compressive strength. It is categorized depending on the characteristic compressive strength $f_{ck}$ (28 days maturity): for normal strength concrete (NSC) $f_{ck} \leq 50$ MPa; for high strength concrete HSC, $f_{ck} > 50$ MPa.

- **Tensile strength**: Tensile strength is significantly lower compared to compressive strength, therefore concrete is usually reinforced with materials that are strong in tension (often steel). Uniaxial tensile testing $f_{ct,d}$ is the most appropriate to evaluate the tensile strength, but there are experimental difficulties; thus splitting tensile strength $f_{ct,sp}$ or flexural tensile strength $f_{ct,fl}$ are used.

- **Stiffness**: The elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develops. The modulus of elasticity ($E_t$) depends on the composition of the concrete (especially the type of aggregate) and ranges from 27.1 GPa for C12 to 22.9 GPa to 50.3 GPa for C120. Poisson’s ratio is set to 0.20.

- **Fracture energy**: $G_F$ [N/m] energy required to propagate a tensile crack of unit area (it describes the resistance of concrete subjected to tensile stresses). It depends on the water/cement ratio, the maximum aggregate size, the age of concrete, and the curing conditions.

For stress–strain relations, it should be considered that an increase of the compressive strength leads only to a small increase of the tensile strength; moreover, the development of tensile strength with time is strongly influenced by curing and drying conditions. In compression, concrete tends to soften as a consequence of the micro-cracking, whereas in tension, a discrete phenomenon happens: at tensile stresses of about 90% of $f_{ck}$, microcracking starts to reduce the stiffness in a small failure zone, micro-cracks grow and form a discrete crack. Therefore, the stress-strain relation is valid and can be used just for un-cracked concrete, whereas for cracked section the stress-crack opening relation should be used.

**Cracking and deformation**

Creep is separated into the basic shrinkage and the drying shrinkage. Basic shrinkage occurs when concrete is subjected to long-duration loading, due to its ageing linear viscoelastic nature. Creep depends on: characteristic compressive strength; dimensions of the member; mean relative humidity; age at loading; duration of loading; and type of cement. Drying shrinkage occurs when concrete transforms from its plastic state, hydrating to a solid. Plastic shrinkage cracks occur soon after placement, but also during finishing operations as well, especially if the evaporation rate is high. Cracking and deformation are also due to temperature effects; however, concrete has a very low coefficient of thermal expansion: $\alpha_T = 10\cdot10^{-6}$ K$^{-1}$ for normal weight concrete, and $\alpha_T = 8\cdot10^{-6}$ K$^{-1}$ for lightweight aggregate concrete.

All concrete structures will crack to some extent, due to shrinkage and tension, independently on if it the compressive strength is enough. Thus, there are two main areas of concern: limiting the cracking and deformation arising from early-age thermal movement, creep, shrinkage, etc; and minimizing the restraints on structural components specifying the joints between the precast elements and the related substrate (PCI Industry Handbook Committee, 2004).
3.1.1. Durability

Durability of concrete is determined by the transport of aqueous and gaseous substances in the pore system and their interaction with the hydrated paste matrix, the aggregate, or the steel reinforcement. Below are explained some physical and chemical properties of the concrete related to the concept of durability.

- **Transport of liquids and gases**: decisive factor concerning concrete durability, it is difficult to predict; depending on concrete composition (e.g. w/c), type of materials (e.g. cement, pozzolanic additives), age, curing, and moisture content; related to the microstructure (e.g. transport coefficients slightly lower in lightweight concrete)
- **Permeation**: flow of liquids or gases caused by a pressure head. *Water permeability*: occurs in the capillary pores and through internal micro-cracks; high permeability caused by insufficient curing. *Gas permeability*: essentially influenced by the moisture content
- **Diffusion**: *Gases diffusion*: (e.g. air, oxygen, carbon dioxide) primarily controlled by the moisture content of the concrete. *Diffusion of chloride ions*: increases with increasing moisture; transported not only by diffusion but also by capillary suction.
- **Capillary suction**: regarding liquids; strongly influenced by the moisture content of the concrete.

Indirect degradation is caused by: carbonation-induced corrosion of reinforcing steel or chloride-induced corrosion of reinforcing steel. Direct degradation is caused by: freeze-thaw attack (internal damage, scaling); reactivity of aggregate and/or of the cement paste (internal damage); acid action (dissolving action). The most detrimental attacks likely to occur are: the alkali-aggregate reaction, which causes the expansion of the aggregate by the formation of a swelling gel of silicate hydrate; the permeation of chlorides in concrete from sea water or other saline contaminated water, which leads to pitting corrosion of the reinforcement.

To ensure the durability of concrete during its design life, it is necessary to specify a suitable concrete mix and to provide sufficient concrete cover. A right mix reduces the permeability of concrete whereas concrete cover protects the reinforcement in accordance with the expected exposure condition and fire resistance requirements.

3.1.2. Design

There is a large literature when it comes to design concrete structures, thanks to the fact that concrete has been the main building material all over the last century; thus, big producers and technicians have been founding many researches. Here listed some main design methods:

- Analysis based on linear elasticity
- Analysis according to linear elasticity with limited redistribution
- Theory of plasticity
- Non-linear analysis

Below are listed the main dimensioning values of the concrete used for the structural design (Table B-3)

- **Characteristic (5%) cylinder strength** \( f_{ck} \) and **cube strength** \( f_{ck,cube} \) at an age of 28 days
- **Tensile strength** \( f_{ctm} \), determined directly by a uniaxial tensile test or indirectly by a splitting tensile test.
- **Flexural tensile strength**, formulated as a function of the axial tensile strength.
• Elastic deformation $E_{cm}$, largely depending on concrete composition (especially the aggregates)
• Poisson’s ratio set to $\nu = 0.2$ for uncracked concrete and 0 for cracked concrete.
• Linear coefficient of thermal expansion $\alpha$ generally equal to $10 \cdot 10^{-6} \text{ K}^{-1}$

Table B-3. Strength classes for concrete (fédération internationale du béton (fib), 2013)

<table>
<thead>
<tr>
<th>Concrete grade</th>
<th>C12</th>
<th>C16</th>
<th>C20</th>
<th>C25</th>
<th>C30</th>
<th>C35</th>
<th>C40</th>
<th>C45</th>
<th>C50</th>
<th>C55</th>
<th>C60</th>
<th>C70</th>
<th>C80</th>
<th>C90</th>
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<tbody>
<tr>
<td>$f_{ck}$(MPa)</td>
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<td>55</td>
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<td>75</td>
<td>80</td>
<td>85</td>
<td>95</td>
<td>105</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{ck,100}$(MPa)</td>
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<td>30</td>
<td>35</td>
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<td>75</td>
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<td>6.0</td>
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<tr>
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<td>7.0</td>
<td>7.5</td>
<td>8.0</td>
<td>8.5</td>
</tr>
</tbody>
</table>

In the non-linear structural analysis, to design the cross-sections of structural elements, a choice can be made between two types of compression stress–strain relations ($\sigma_s - \varepsilon_s$) for short term uniaxial loading: the parabola–rectangle relation, or the bilinear stress–strain relation (Figure B-7 b and B-7 c, respectively).

Figure B-7. a) compression stress–strain relations $\sigma_s \cdot \varepsilon_s$; for design: b) the parabola–rectangle relation, c) bilinear stress–strain relation (fédération internationale du béton (fib), 2013)

3.2. Fibre reinforced concrete

Besides the ordinary concrete, a set of value added products (VAPs) exists, which can contribute with properties that ordinary concrete does not have and can help timber to create successful synergy in construction. Nevertheless, these special concretes seem to follow the same destiny of the timber, as they are not successful commercial building materials and demand from the customers is very limited within an extra-ordinary construction market. An interesting category of these VAPs is represented by the fibre

8 (Daniel et al., 2002)
reinforced concrete (FRC), where wood takes part as natural fibre. In the following sections, the main FRCs are presented. Mixtures of different types and/or sizes of fibres can also be used (called hybrid fibre reinforced concrete).

3.2.1. Steel fiber reinforced concrete (SFRC)

Steel fiber reinforced concrete is made of hydraulic cements containing fine or fine-and-coarse aggregate and discontinuous discrete steel fibers. In tension, SFRC fails only after the steel fibers break or are pulled out of the cement matrix. Steel fiber are short, with an aspect ratio (length to diameter) varying from 20 to 100, and are characterized by high strength and high modulus of elasticity. They are bonded to the matrix by mechanical anchorage or surface roughness and are protected from corrosion by the alkaline environment of the cementitious matrix. The main benefit compared to a plain concrete is a higher ductility: fibers impart post-crack ductility to the cementitious matrix (that would otherwise behave and fail in a brittle way) thanks to the gradual nature of the fibers’ pull-out.

Fibers’ effectiveness in improving concrete strength varies among compression, tension, shear, torsion, and flexure:

- **Compression**: ultimate strength slightly affected by the presence of fibers
- **Direct tension**: significant improvement in strength
- **Shear and torsion**: the shear and torsional strength of concrete could be negligible or increase by 30%, depending on the degree of alignment of the fibers in the shear failure zone. The improvement of shear and torsional strength is a potential advantage to augment or replace vertical stirrups in beams
- **Flexure strength**: the improvement in flexural strength is greater than in tension or compression. It is due to the ductile behaviour on the tension side of a beam, which alters the normally elastic distribution of stresses and strains over the member depth; stress distribution is essentially plastic in the tension zone and elastic in the compression zone, resulting in a shift of the neutral axis toward the compression zone.
- **Behaviour under impact loading**: it is registered an increase of the fracture energy under impact; the peak loads for SFRC are about 40 percent higher than those obtained for the plain matrix.
- **Fatigue behaviour**: there is a significant increase in flexural fatigue strength (and decrease of the crack width) by increasing percentage of steel fibers
- **Toughness**: SFRC withstands multiple hammer blows before a hole is punched at the point of impact. Even after the hole has been made, the rest of the sample retains its structural integrity. A SFRC beam would suffer damage by gradual development of cracks with increasing deflection, but would retain some degree of structural integrity and post-crack resistance even with considerable deflection, whereas a similar beam without steel fibers would fail suddenly at a small deflection by separation into two pieces.
- **Thermal conductivity**: there are small increases in the thermal conductivity
- **Corrosion of fibers, cracked concrete**: corrosion of fibers is limited to the surface skin of the concrete (not much more than 2.5 mm); fibers are short, discontinuous, and rarely touch each other; thus, there is no continuous conductive path.
Design considerations

SFRC is essentially a concrete with increased strain capacity, impact resistance, energy absorption, fatigue endurance, and tensile strength. For flexural structural components, steel fibers are generally used in conjunction with properly designed continuous reinforcement, according to a conservative approach: the reinforcing bars must be designed to resist the total flexural or tensile load. Moreover, steel fibers are effective in supplementing or replacing the stirrups in beams. SFRC is attractive for its isotropic strength properties (thanks to the uniform dispersion of the fibers). There are some applications where steel fibers have been used without reinforcing bars to carry loads, after full-scale load tests have been carried out. SFRC slabs would need to be only about one half the thickness of plain concrete slabs for the same loads. Nowadays they are employed for pavements or industrial floors, tilt-up panels, and precast garages.

3.2.2. Glass fiber reinforced concrete (GFRC)

Glass fiber reinforced concrete is made of alkali resistant fibers (AR-glass fibers) that provide improved long-term durability. The methods of production are two: the spray-up process (manufacturing in layers), and the premix process (mixing cement, sand, chopped glass fiber, water and admixtures together into a mortar).

The mechanism primarily responsible for the additional strength and ductility is the fiber pull-out: after the first cracking, much of the deformation is attributed to fiber extension. As load and deformation continue to increase, and multiple cracking occurs beyond the proportional elastic limit, fibers begin to debond and subsequently slip or pull-out to span the cracks and resist the applied load. Load resistance is developed through friction between the glass fibers and the cement matrix as the fibers debond and pull-out. Design procedures exist only for wall panels; these are carried out by considering design stresses occurring in diaphragms and webs: flexural stresses, based on straight line theory of stress and strain in flexure, and shear stresses (direct shear, interlaminar shear, in-plane shear), which seldom controls the design.

About the long-term performance of GFRC, it is registered a reduction of tensile and flexural strengths and ductility (composite embrittlement) during time; this reduction is faster in warmer, more humid climates. To provide improved long-term durability, some polymers are added, which reduce concrete’s absorption and consequently the wet/dry shrinkage movements. Moreover, AR-glass fibers preserve the cement matrix against freeze-thaw deterioration. Another advantage is that GFRC is a non-combustible material (the flame spread index is zero).

It is necessary to eliminate restraints from the GFRC elements by using flexible connections (flex-anchor or gravity anchor), to accommodate the dimensional changes (as creeps, thermal and moisture movements) in the structural frame of the building. Moreover, in surface finishes, it is necessary to provide a bond breaker between the veneer and the GFRC skin for their differential moisture and thermal movements. Surface finishes made of GFRC are often used for their aesthetics appeal, since GFRC follows closely the surface texture or pattern of the mould, has many colour variations, and resembles to natural stone veneers.

Nowadays GFRC are employed for many applications:

- Exterior building facade panels and architectural cladding: interior/exterior panels, single/double skin (thermally insulated), aesthetical paint, tile, aggregate facings
- Building restoration: replacement of existing walls and ornate tile facades (light weight and shape versatility)
- Architectural component: doors and door frames, windows, sub-frames, sills
- Interior fixtures: prefabricated bathroom units, lavatory units, bench tops, shelving, shells
- General building: hollow non-structural columns or pillars, impact resistant industrial floors, brick facade siding panels, cellular concrete slabs, prefabricated floor and roof units, site-applied surface bonding
- Small buildings and enclosures: sheds, garages, acoustic enclosure
- Bridge decking formwork, parapets, abutments, waffle forms, columns and beams
- Electrical utility products as ducts and shafts
- Fire protective system: fire doors, internal fire walls, partitions, calcium silicate insulation sheets

3.2.3. Synthetic fiber reinforced concrete (SNFRC)

Synthetic fibers are used to increase the toughness and the load-carrying capabilities of the concrete matrix after the first crack; thus, for SNFRC, unaffected strength and crack control characteristics are sought. Fibers’ length and configuration, as well as their spacing and surface area, are the key parameters influencing the behaviour of FRC. The average fiber spacing (number of fibers crossing a unit area in an arbitrary composite cross section) affects rheological properties of the mix and mechanical properties of the hardened concrete. The fiber specific surface (FSS) is the predominant factor determining crack spacing and crack width: the greater the FSS, the closer the crack spacing and the narrower the crack width. Fiber decomposes when reaching its melting point, sometimes even before because of possible chemical reactions (e.g. oxidation). Physical and chemical properties of synthetic fibers - and thus their durability and chemical compatibility in the encapsulating matrix - must be individually determined (Table B-4).

**Table B-4. Selected synthetic fiber types and properties. (Not all fiber types are currently used for commercial production of FRC) (Daniel et al., 2002)**

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Equivalent diameter, in. x 10^{-4}</th>
<th>Specific gravity</th>
<th>Tensile strength, ksi</th>
<th>Elastic modulus, ksi</th>
<th>Ultimate elongation, percent</th>
<th>Ignition temperature, degrees F</th>
<th>Melt, oxidation, or decomposition temperature, degrees F</th>
<th>Water absorption per ASTM D 795, percent by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>0.5-4.1</td>
<td>1.10-1.18</td>
<td>39-145</td>
<td>2000-2800</td>
<td>7.5-50.0</td>
<td>—</td>
<td>430-455</td>
<td>1.6-2.5</td>
</tr>
<tr>
<td>Aramid I</td>
<td>0.47</td>
<td>1.44</td>
<td>425</td>
<td>9000</td>
<td>4.4</td>
<td>high</td>
<td>900</td>
<td>4.3</td>
</tr>
<tr>
<td>Aramid II</td>
<td>0.40</td>
<td>1.44</td>
<td>340</td>
<td>17,000</td>
<td>2.5</td>
<td>high</td>
<td>900</td>
<td>1.2</td>
</tr>
<tr>
<td>Carbon, PAN HAT</td>
<td>0.30</td>
<td>1.6-1.7</td>
<td>360-440</td>
<td>55,100</td>
<td>6.0-6.7</td>
<td>high</td>
<td>752</td>
<td>nil</td>
</tr>
<tr>
<td>Carbon, PAN HFT</td>
<td>0.35</td>
<td>1.6-1.7</td>
<td>500-580</td>
<td>33,400</td>
<td>1.6-1.5</td>
<td>high</td>
<td>752</td>
<td>nil</td>
</tr>
<tr>
<td>Carbon, pitch GFP</td>
<td>0.39-0.51</td>
<td>1.6-1.7</td>
<td>70-115</td>
<td>4000-5000</td>
<td>2.6-2.4</td>
<td>high</td>
<td>752</td>
<td>3.7</td>
</tr>
<tr>
<td>Carbon, pitch HP</td>
<td>0.35-0.70</td>
<td>1.6-2.15</td>
<td>220-450</td>
<td>22,000-70,000</td>
<td>0.5-1.3</td>
<td>high</td>
<td>932</td>
<td>nil</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.90</td>
<td>1.14</td>
<td>140</td>
<td>750</td>
<td>30</td>
<td>—</td>
<td>397-430</td>
<td>2.8-5.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.78</td>
<td>1.34-1.39</td>
<td>33-160</td>
<td>2500</td>
<td>12-150</td>
<td>1100</td>
<td>495</td>
<td>0.4</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.5-4.0</td>
<td>0.92-0.99</td>
<td>11-55</td>
<td>725</td>
<td>3-80</td>
<td>—</td>
<td>275</td>
<td>nil</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.6-4.0</td>
<td>0.90-0.91</td>
<td>20-100</td>
<td>500-700</td>
<td>15</td>
<td>1100</td>
<td>330</td>
<td>nil</td>
</tr>
</tbody>
</table>

*Not all fiber types are currently used for commercial production of FRC.
*High modulus.
*Polypropylene-based, high modulus.
*Polyurethane-based, high tensile strength.
*Polyurethane-based, high modulus.
*Polyethylene pitch-based, high performance.
*Polyurethane pitch-based, high performance.

- **Acrylic**: relatively high tensile strength and high tensile modulus; dimensional stability; creep resistance; “green strength” allowing immediate handling.
- **Carbon**: high tensile strength and high elastic modulus; inert to most chemicals; expensive
- **Nylon**: good tenacity, toughness, and excellent elastic recovery; heat stable, relatively inert material, resistant to a wide variety of organic and inorganic materials including strong alkalis; difficulty in
obtaining a satisfactory mix because of the large surface area of the fibers; significant improvement in impact strength (effective in controlling the impact forces in a blast situation), fracture toughness (ability to absorb energy in the post-crack region), ductility, dimensional stability (control of cracking: reduction in creep strain, ability to reduce concrete shrinkage), effectiveness in increasing the load carrying capability of concrete following first crack: improved toughness and crack control after exposure to an accelerated aging environment.

- **Polyethylene**: hydrophobic; low melting point and low elastic modulus; limitations in certain processes such as autoclaving; early strength enhancement; control of thermal and moisture changes (thanks to a system of “relief channels” created in the matrix when the fibers disappear at high temperatures; improved material toughness); improved toughness and crack control properties for some fiber types; linear flexural deflection behaviour up to first crack.

- **Polyester**: control of plastic shrinkage-induced cracking

- **Polypropylene**: compressive strength: unchanged compared to the plain concrete, but more ductile failure mode; flexural strength slight increased ; impact strength: increase (33 to 1000 percent) according to the fiber content; fatigue strength and endurance limit: increase according to the fiber content; flexural toughness and post-crack behaviour: ability to absorb elastic and plastic strain energy and to conduct tensile stresses across multiple matrix cracks; shrinkage and cracking ability: control of drying shrinkage (after cracking, polypropylene fibers transfer tensile stress across cracks and arrest or confine crack tip extension, so that many hairline cracks occur instead of fewer larger cracks).

Many applications of SNFRC regard cast-in-place concrete (e.g. slabs-on-grade, pavements, and tunnel linings) and factory products (e.g. cladding panels, siding, shingles, and vaults):

- **Applications of carbon FRC**: corrugated units for floor construction, single and double curvature membrane, structures, boat hulls, scaffold boards, free access floor systems, lightweight carbon FRC with micro-balloons as aggregate, FRC curtain walls; high cost, but structural applications appear promising;

- **Applications of polypropylene and nylon FRC**: non-structural and non-primary load bearing applications such as industrial slabs on grade, slabs for composite metal deck, floor overlays, precast units, slip form curbs, mortar applications.

### 3.2.4. Natural fiber reinforced concrete (NFRC)

Natural fiber reinforced concrete can be made of two types of fibers:

- **Unprocessed natural fibers (UNF)**: Discontinuous, short, naturally occurring fibers for reinforcing concretes, mortars and cements. Their use is enhanced by locally available manpower and technical know-how; small amount of energy is required.

- **Processed natural fibers (PNF)**: Natural fibers processed to enhance their properties. They derived from wood by chemical processes (e.g. kraft process) to make thin sheet with high fiber content.

Some of the most important UNFs (Table B-5):are made of: coconut fiber; sisal fiber (gypsum plaster sheets); sugar cane bagasse fiber; bamboo fiber (strong in tension, can be used as a reinforcing material, high water absorption capacity, low modulus of elasticity); jute fiber (strong in tension); flax (extremely high tensile strength and modulus of elasticity).
Table B-5. Typical properties of natural fibers (Daniel et al., 2002)

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Coconut</th>
<th>Sisal</th>
<th>Sugar cane Bagasse</th>
<th>Bamboo</th>
<th>Jute</th>
<th>Flax</th>
<th>Elephant grass</th>
<th>Water reed</th>
<th>Plantain</th>
<th>Musimba (wood pulp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, in.</td>
<td>2-4</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>7-12</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Diameter, in.</td>
<td>0.904-</td>
<td>N/A</td>
<td>0.908-0.916</td>
<td>0.902-</td>
<td>0.904-0.908</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.001-0.003</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.1-1.15</td>
<td>N/A</td>
<td>1.2-1.3</td>
<td>1.5</td>
<td>1.02-1.04</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Modulus of</td>
<td>2750-</td>
<td>1880-</td>
<td>2770</td>
<td>2750-27</td>
<td>4700-5800</td>
<td>3770-4640</td>
<td>14,500</td>
<td>710</td>
<td>750</td>
<td>200</td>
</tr>
<tr>
<td>elasticity, ksi</td>
<td>3770</td>
<td>2770</td>
<td>2770</td>
<td>2770</td>
<td>3770-4640</td>
<td>14,500</td>
<td>710</td>
<td>750</td>
<td>200</td>
<td>130</td>
</tr>
<tr>
<td>Ultimate tensile</td>
<td>17,400-</td>
<td>40,000-</td>
<td>62,400</td>
<td>26,650-</td>
<td>30,720-72,500</td>
<td>36,250-50,750</td>
<td>145,000</td>
<td>25,800</td>
<td>10,000</td>
<td>13,300</td>
</tr>
<tr>
<td>strength, psi</td>
<td>29,000</td>
<td>3770</td>
<td>3770</td>
<td>3770</td>
<td>3770-4640</td>
<td>14,500</td>
<td>710</td>
<td>750</td>
<td>200</td>
<td>130</td>
</tr>
<tr>
<td>Elongation at</td>
<td>10.25</td>
<td>3.5</td>
<td>N/A</td>
<td>N/A</td>
<td>1.5-1.5</td>
<td>1.8-2.2</td>
<td>3.6</td>
<td>1.2</td>
<td>5.9</td>
<td>9.7</td>
</tr>
<tr>
<td>break, percent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water absorption,</td>
<td>130-180</td>
<td>60-70</td>
<td>70-75</td>
<td>40-45</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>percent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: N/A = properties not readily available or not applicable.
Metric equivalents: 1 in. = 25.4 mm; 1 ksi = 1,000 psi = 6.895 MPa

PNFs are usually made by “pulping”, that consists in processing the plant materials to extract the fibers. Especially trees are used: the bond between fibers is broken into solid softwoods and hardwoods thanks to a mechanical, chemical, or semi-chemical process. Wood removed in the chemical process is susceptible to alkalas and is therefore responsible for the degradation of the concrete matrix; thus, chemical pulps (kraft) are more commonly used for the reinforcement of cement. The cellulose, that is the primary chemical constituent of natural fibers, exhibits a tensile strength of approximately 6.400 MPa. Among commercial trees, softwoods are the source of the so-called long fibers with typical lengths ranging from 2 to 7 mm.

The type and length of fibers and their volume fraction are the most significant factors influencing the properties of the UNFRC. The minimum fiber addition to provide some mechanical improvement is about 3 percent by volume; however, the impact resistance is increased regardless of the fiber volume fraction. The fresh concrete suffers from reduced workability; moreover, fibers should be put at the end of the mixing process to avoid “balling” effects which would be detrimental for the strength of the concrete. Once hardened, the concrete has adequate strength but is brittle; the compressive strength is not significantly affected, but the tensile and flexural strength and the toughness are substantially increased. Some deficiencies are registered in the durability because of the swelling of fibers in presence of moisture. The UNFRC is more vulnerable than other FRCs in terms of durability, due to the highly alkaline pore-water.

The performance of PNFRCs (the flexural strength and toughness) in both short-term and long-term periods depends on the methods used for the curing and the mix proportions. By increasing the fiber content, the density of the composite decreases and the void volume increases (but in a non-linear fashion) with a consequent increase of moisture content, which tends to decrease the flexural strength and increase the flexural toughness. The durability of PNRC (e.g. kraft pulp) seems to increase upon weathering (moisture and aggressive environments change the failure mechanisms and thus affect the strength and the toughness in cellulose-cement composites). More researches regarding the potential for embrittlement consistent with the weathering are needed.
Natural fiber reinforced concrete is employed to make thin cement sheets for walls and roofs, suitable for low-cost constructions with a short durability (about 10 years). In Africa, sisal is used for roof tiles, corrugated sheets, pipes, silos, and tanks. In Zambia, elephant grass mortar and cement sheets are used for low-cost house construction, whereas wood and sisal fibers are used for cement composite panel lining, eaves, soffits, and for sound and fire insulation. Wood fibers derived from the kraft process have highly desirable performance-to-cost ratios; they are used to make thin flat or corrugated sheets, non-pressure pipes, and cable pit.

3.2.5. Design

The main advantage of adding fibres to concrete or mortar is that they generate a post-cracking residual tensile strength in combination with a large tensile strain; thus, FRC is characterized by substantial ductility and toughness. Elastic properties and compressive strength are not significantly affected by fibres, unless a high percentage is used.

Fibres are active as soon as micro-cracks are formed in the concrete; thereby, structural design of FRC elements is based on the post-cracking residual strength provided by fibre reinforcement. Other aspects, such as early age crack-control and fire resistance, are considered. Fibres can be used to improve the behaviour at serviceability limit state (SLS) reducing crack spacing and crack width (thereby improving durability), or to improve the behaviour at ultimate limit state (ULS), partially or totally substituting conventional reinforcement.

Depending on their composition, FRC can show hardening or softening behaviour under uniaxial tension (Figure B-8):

- softening behaviour (a): the deformations localize in one crack.
- hardening behaviour (b): multiple cracking occurs before reaching the peak value

Generally, in compression the relations valid for plain concrete apply to FRC as well; however, fibres can reduce the brittleness of concrete in compression and lead to a ductile failure.

![Figure B-8. Softening (a) and hardening (b) behaviour in axial tension; c) main differences between plain and fibre reinforced concrete having both normal and high strength under uniaxial compression (Consiglio Nazionale delle Ricerche, 2012)](image)

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9 (Rilem TC 162-TDF, 2002; Consiglio Nazionale delle Ricerche, 2012)
3.3. Special concretes

Besides FRCs, other value-added products exist. Here are listed the main ones:

- **Green concrete**: is concrete made by replacing the aggregates with chemically reactive or inert fine materials (e.g. fly ash, silica fume, blast furnace slag, natural pozzolans) in order to obtain a more sustainable product. The modulus of elasticity suffers from a reduction at early age and a further gain at higher ages (fédération internationale du béton (fib), 2013).

- **3D biaxial textile reinforcement** is used to make lower net weight and thinner construction elements, with reduction of steps in the process of casting the concrete and applying the textile reinforcement. A wide variety of fibre materials can be used in the reinforcement: fibre glass, basalt, aramid, carbon fibres. This concrete has high flexible, tensile and impact-resistant strength, as well as higher insulation properties (Fraas, 2013).

- **Self-healing concrete**: there are three types of self-healing concrete: one with shape-memory polymers activated by electrical current; one with healing agents made from organic and inorganic compounds; and one with capsules containing bacteria and healing agents (World architecture news, 2016).

- **Water drinker concrete**: it has a permeable layer on top that allows the water to drain through a matrix of large pebbles and then go down into a loose base of rubble beneath (Matchar, 2015).

- **Smog eating concrete**: it is a photocatalytic concrete with nano-particles of titanium dioxide that “eat” smog by removing the nitrogen oxide gasses from the surrounding air and expelling hydrogen dioxide in its place (Lee, 2016).

4. Recapitulatory tables

In the tables in the following pages are summarized the main information about timber and concrete and their relative construction products.
<table>
<thead>
<tr>
<th><strong>TIMBER</strong></th>
<th><strong>General</strong></th>
<th><strong>Glulam</strong></th>
<th><strong>CLT</strong></th>
<th><strong>LVL</strong></th>
<th><strong>Plywood</strong></th>
<th><strong>Strands, chips, fibres EWPs</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturing</strong></td>
<td>Several lamellas glued together in the same direction</td>
<td>Uneven number of layers resulting in one main spanning direction</td>
<td>all the layers oriented with the same fibre direction</td>
<td>veneers laid up perpendicular to each other; normally fibre direction oriented in the long direction of the panel</td>
<td>OSB: wood strands sliced pressed together using adhesive. In the outer layers, strands are oriented parallel to the long direction; in the inner layer, strands are randomly-oriented</td>
<td></td>
</tr>
<tr>
<td><strong>Density:</strong> $\rho_2 = 300 - 600 \text{ kg/m}^3$</td>
<td></td>
<td>Lower variability in strength</td>
<td>Bidirectional bearing capacity; effective lateral load resisting system. Design influenced by ductility</td>
<td>Higher reliability and lower variability</td>
<td>layered glued veneers form stability though cross-wise built-up</td>
<td></td>
</tr>
<tr>
<td><strong>Tension parallel to the fibre direction:</strong> very high (up to 100 MPa) failure often very brittle.</td>
<td></td>
<td>Tensile failure: tensile stress parallel to the grain in the outer lamination are the most common failure</td>
<td>Design controlled by serviceability criteria (flexural stiffness)</td>
<td></td>
<td>The layers with grain direction in the same direction as the normal stresses have the highest stiffness and take the major part of the load; Contribution to the load bearing of the layers with grain direction perpendicular to the direction of the normal stresses can be disregarded</td>
<td></td>
</tr>
<tr>
<td><strong>Shear strength:</strong> highest in planes parallel to the fibre $\tau_{90}$ and $\tau_{45}$ (respectively 5 and 8 MPa); rolling shear, perpendicular to the fibre direction $\tau_{0}$ about 3-4 MPa</td>
<td></td>
<td>Important to consider shear flexibility due to rolling shear</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Moisture:</strong> strength affected differently depending on the loading directions. Variation for 1% change in moisture content: 5% change in compression parallel and perpendicular to the grain, 2% change in tension parallel and perpendicular to the grain, 4% change in bending</td>
<td>locking of moisture movements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Time effect:</strong> increase in strength; creep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fire:</strong> Slowly char at a predictable rate, little info on creep and vibration; more prone to creep than other EWP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Post and beams structures, long-span pavilions (also curved)</td>
<td>Load-bearing vertical walls and horizontal floor diaphragms, single curved elements, 3d box elements</td>
<td>Panels, beams</td>
<td>Sheathing, facade panels (if treated), structural stabilization, interior applications</td>
<td>OSB: in walls or in floor structures, beams, wall diaphragms, roof elements Fiber boards: I beams, walls, and roof diaphragms Particle boards (chipboards): intermediate floor layer, interior cladding, furniture</td>
<td></td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>SFRC</td>
<td>GFRC</td>
<td>SMFRC</td>
<td>NFRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>------</td>
<td>------</td>
<td>-------</td>
<td>------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compressive strength:</strong></td>
<td>20-30 MPa</td>
<td>20-30 MPa</td>
<td>20-30 MPa</td>
<td>20-30 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tensile strength:</strong></td>
<td>1.5-3.0 MPa</td>
<td>1.5-3.0 MPa</td>
<td>1.5-3.0 MPa</td>
<td>1.5-3.0 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shear strength:</strong></td>
<td>0.5-1.0 MPa</td>
<td>0.5-1.0 MPa</td>
<td>0.5-1.0 MPa</td>
<td>0.5-1.0 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flexural strength:</strong></td>
<td>5.0-10.0 MPa</td>
<td>5.0-10.0 MPa</td>
<td>5.0-10.0 MPa</td>
<td>5.0-10.0 MPa</td>
<td></td>
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</tr>
<tr>
<td><strong>Impact strength:</strong></td>
<td>10-20 kJ/m²</td>
<td>10-20 kJ/m²</td>
<td>10-20 kJ/m²</td>
<td>10-20 kJ/m²</td>
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<table>
<thead>
<tr>
<th>Long-term Performance</th>
<th>SFRC</th>
<th>GFRC</th>
<th>SMFRC</th>
<th>NFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Durability:</strong></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Long-term performance:</strong></td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
</tr>
<tr>
<td><strong>Impact resistance:</strong></td>
<td>High</td>
<td>High</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Applications</th>
<th>SFRC</th>
<th>GFRC</th>
<th>SMFRC</th>
<th>NFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pavements or industrial floors:</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Building facade panels:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Electrical utility products:</strong></td>
<td></td>
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<tr>
<td><strong>Building restoration:</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Fire performance:</strong></td>
<td>Non-combustible material (null flame spread index)</td>
<td></td>
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<tr>
<td><strong>Weatherability:</strong></td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
<td>High tensile strength, high toughness, and ductility</td>
</tr>
<tr>
<td><strong>Cost:</strong></td>
<td>High</td>
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<table>
<thead>
<tr>
<th>Temperature effects:</th>
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<th>GFRC</th>
<th>SMFRC</th>
<th>NFRC</th>
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</thead>
<tbody>
<tr>
<td><strong>Relative humidity:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shrinkage and cracking:</strong></td>
<td>Crack control depending on the fiber type</td>
<td>Crack control depending on the fiber type</td>
<td>Crack control depending on the fiber type</td>
<td>Crack control depending on the fiber type</td>
</tr>
<tr>
<td><strong>Fire resistance:</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Cost:</strong></td>
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<table>
<thead>
<tr>
<th>Density:</th>
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<th>GFRC</th>
<th>SMFRC</th>
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<tbody>
<tr>
<td><strong>Normal weight concrete:</strong></td>
<td>2000-2600 kg/m³</td>
<td>2000-2600 kg/m³</td>
<td>2000-2600 kg/m³</td>
<td>2000-2600 kg/m³</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost:</th>
<th>SFRC</th>
<th>GFRC</th>
<th>SMFRC</th>
<th>NFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete:</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
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</tbody>
</table>
1. References


