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Timber high rise, state of the art

Madera en altura, estado del arte

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ABSTRACT

This article is focused on analysing the current situation of timber high-rise construction. It begins with a historical review from the traditional Pagodas (up to 63 m tall) to visions of the future that rises to 350 m. It states the technical development that has led mass timber to today's engineered products and its researches. It displays timber's behaviour to fire and its properties as a structural material compared to others more commonly used in high-rise construction. It proves to be as mechanically competitive as concrete or high strength steel. Different strategies can be used against horizontal forces to obtain maximum slenderness. However, its main advantage, from an ecological point of view, is its capacity to absorb CO_2, which, along its high degree of prefabrication, makes it a sustainable alternative with an increasing acceptance.

Keywords: Timber, high rise, glulam, cross laminated timber, sustainability, fire behaviour, slenderness, CO_2 emissions.

RESUMEN

El objetivo es mostrar el panorama actual de la edificación en altura con madera. Comienza con una revisión histórica desde las pagodas orientales (hasta 63m de altura) hasta las visiones de futuro (350m). Se muestra el desarrollo tecnológico que ha llevado la madera maciza hasta los productos industrializados actuales y las investigaciones en desarrollo. Se expone su comportamiento ante el fuego y las propiedades como material estructural en comparación con los materiales estructurales más utilizados para la edificación en altura: mecánicamente es tan competitivo como hormigones o aceros de alta resistencia. Ante acciones horizontales hay varias estrategias y se obtienen las esbelteces máximas alcanzables en altura. Su principal ventaja, desde el punto de vista ecológico, es su capacidad de absorber CO_2, lo que, junto con el alto nivel de prefabricación, lo convierte en una alternativa sostenible cada vez con mayor aceptación.

Palabras clave: *Madera, edificio en altura, madera laminada, madera contralaminada, sostenibilidad, comportamiento ante el fuego, esbeltez, emisiones CO_2.*

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1. INTRODUCTION

When speaking about the first high rise buildings, it is common to refer to Chicago's brickwork buildings. One of the most representative buildings from this stage is the Monadnok (1891) that rises 60 m. However, wooden buildings had already surpassed this height previously. Therefore, the first high rises were made from timber.

The evolution of engineered timber during the XX century has made some architects name it "the material of the XXI century" (1). Currently the main advantage of timber as structural material lies in its ecological properties. In this article this advantage is exposed, such as its ability to absorb CO2, but also considering whether deforestation is a threat as the material's demand increases. It shows similar strength properties compared to structural materials frequently used nowadays. The properties of this construction method will also be shown. Finally, the article reviews the high-rise timber buildings recently completed (up to 57.9 m), the ones that are being constructed (up to 84 m) and the visions of the future that expect to reach 350 m by the year 2041.

2. HISTORICAL REVIEW

2.1. From the Roman Insulaes to eastern Pagodas

Timber has been linked to architecture ever since humanity decided to leave the cave. As architecture moved forward so has done the knowledge and technics surrounding this material. Even in the ancient Rome, well-known for its brick, stone and marble architecture, architects found in timber a solution for its overcrowded capital: the *Insulae*. This building typology was composed by a commercial base made of brickwork and a main body of apartments with a timber structure. The lightness of wood allowed these buildings to rise higher, up to 6 floors. The building codes enacted during the time of Julius Cesar to limit construction heights up to 21 m prove that such heights were possible (2).

Asian architecture also used timber for its highest religious temples: Pagodas. This illustrates the durability of timber when it is well treated and taken care of. The Horyu-Ji religious complex host a 32.55-meter-high pagoda (Figure 1) that dates to the year 711 AC. It is still standing even though it is located in Nara, Japan, known for being a seismic region. Even the Kobe earthquake of 1995, that scored 6.9 in the Richter scale, wasn't able to produce any structural damage. The structure of pagodas is composed by 2 parts, a mass timber central column (Shin-Bashira) and several storeys of timber frameworks (3). While the Shin-Bashira is isolated from the rest of the structure by 1 cm gaps, the surrounding timber structure is made of individual storeys that rest on top of each other. The combination of both strategies allows the structure to dissipate the oscillatory movement produced by earthquakes.

This tipology spread across Japan reaching heights over 50 meters (Figure 1). However, the highest historical timber pagoda that has survived to this day is Sakyamuni with a height of 67.31m. Built in 1056 AC, in the county of Yingxian, China, another seismic region, but with a different strategy. In this case, the stony base of 4m moves with the soil, and the oscillating part is reduced to 63m, remains a very important height.

2.2. Timber abandonment

Although the predominant material for structures in conventional architecture has been timber, it reached the XX century as a discredited material (4). Wood is easily associated with tragedies, such as the Great Fire of London in 1666, which prompted the first regulations against timber use in construction, or more recently the Great Chicago Fire in 1871 and the fire following the San Francisco Earthquake in 1906. All of them important cities linked to industrial development, that decided to trust in brick and stone, and later in concrete and steel, instead of timber. Therefore, timber was left out of the cities and relegated to rural architecture (5).

However, its actual downfall came by the hand of the industrial revolution. The timber industry wasn't strong enough to take advantage of it. Besides, the development of materials as concrete and steel soon took over the construction industry thanks to its uniform and predictable behaviour. Something that wood couldn't assure due to its natural background.

Iron and steel were materials that existed before the industrial revolution. However, this movement led to a democratiza-

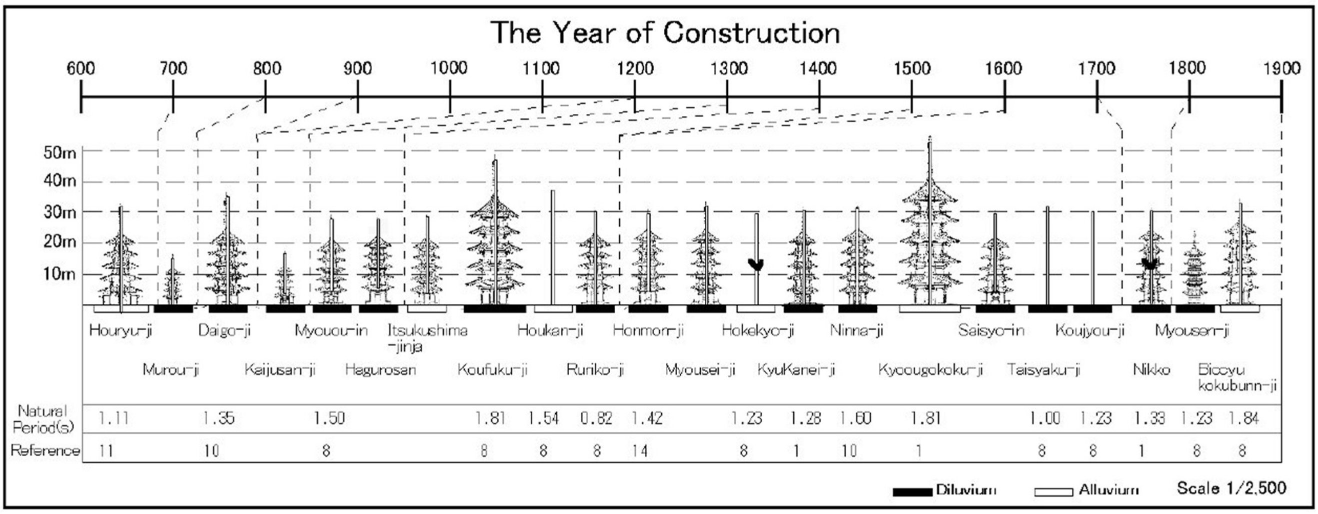

Figure 1. 5-storey pagoda's corss-sections built in Japan before 1850 (3).

tion of these materials thanks to the new production methods that made it a cheaper and faster process. Both materials had a rapid development and acceptance in the industry, while timber barely evolved. At the same time, in Chicago the race to conquer the sky had already begun. A race boosted by the improvements made on elevator's security and the reinforcement of these new materials.

3. THE FIRST HIGH RISES

High-rise buildings arose in response to the exponential growth of population that cities experienced in the late XIX century. As well as the creation of finance districts in cities at the forefront of development. This situation increased the need of space in cities like New York or Chicago, especially after the 1871 fire. *"The disaster, combined with increased urban land values, the invention of the elevator, and the development of structural steel, gave rise to the skyscraper."* (6)

Steel frame structures rapidly replaced brickwork bearing wall systems. In 1883, the Home Insurance Building set the first step with a height of 42m. In less than 100 years, in the same city of Chicago, skyscrapers reached heights 10 times higher with the 442-meters-high Sears Tower. And 30 years after that, in the Middle East, the Burj Khalifa doubled this height becoming the tallest building at 828 meters. The race for height is briefly summarised in the Table 1.

Many have cirticised high-rise buildings because of their high costs, their impact in their surroundings or its excessive energy demand. However, the energy consumed by high-rises is less than the energy that would be needed for an equivalent capacity in low-rise buildings (7). Besides, technological breakthroughs are making high rises more efficient, reducing global energy conssumption (8). Therefore, a controlled vertical growth of cities is more sustainable than horizontal sprawl.

Table 1. Buildings that held the world tallest building title and location (9).

Date	Building	Height	Location
1885	Home Insurance Building	55 m	Chicago, Illinois
1890	World Building	94 m	New York City
1894	Manhattan Life Insurance Building	106 m	New York City
1899	Park Row Building	119 m	New York City
1908	Singer Building	187 m	New York City
1909	Metropolitan Life Tower	213 m	New York City
1913	Woolworth Building	241 m	New York City
1930	40 Wall Street	283 m	New York City
1930	Chrysler Building	319 m	New York City
1931	Empire State Building	381 m	New York City
1972	1 World Trace Center	417 m	New York City
1974	Sears Tower	442 m	Chicago, Illinois
1998	Petronas Towers	452 m	Kuala Lumpur, Malaysia
2004	Taipei 101	509 m	Taipei, Taiwan
2009	Burj Khalifa	828 m	Dubai, EAU

The 9/11 attack produced a huge impact in how we build high-rises. Steel, the most used structural material until then, was soon replaced by reinforced concrete because of fire safety reasons. These circumstances along with the great performance of reinforced concrete left steel to a secondary role used only in combined structures with concrete (9). However, both materials produce a huge amount of pollution.

The interest in reducing the ecological impact has prompted the search for more efficient and less pollutant solutions (8). It is in this feature were timber outperforms both materials.

4. REVIVAL: ENGINEERED TIMBER

Philibert de l'Orme (1515-1577) started to divulge the use of small-sized pieces to form longer elements. Later, Armand Emy (1771-1851) was the first to use laminated timber with jointed by nails and collars. However, these joints weren't enough to make the different layers of timber work as a whole. Otto Hetzer (1846-1991) revolutionised the timber industry with his patents (10, 11). Hetzer registered in 1906 a patent where the equivalent to Glue Laminated Timber (Glulam) appeared for the first time. Glulam is based on the concept of merging multiple layers of lumber to create a unified wooden structural element of larger dimensions. The first Glulam building was erected in 1934 (Figure 2).

Figure 2. Forest Products Laboratory, Minneapolis (10).

The introduction of glue as the adhesive allows to maximize the contact surface which led to an increase in the resistance to shear forces between layers. Anyway, for the glued joint to be able to transfer these forces between members it needs to be stronger than the timber itself (10).

The first adhesives where casein compounds which aren't water resistant. This limitted its use only to dry interiors. It wasn't until 1936 that formaldehids where introduced, which led to higher performances, eventually reaching solid timber's performance. However, they were later substituted by urea-formaldehids due to its transparency (12). Thanks to these adhesives the performance of glulam has become similar to non-engineered lumber. In his first steps, to avoid joints perpendicular to the grain, Otto Hetzer had to use timber laths with the same length as the final product. This limited the length of the outcome piece to 15 meters. However, in 1942 the first finger joints were made (13). Finger joints provide these uncomfortable joints a broad Surface area for gluing timber's grains at an oblique angle. Timber specialists (14) classify this joint as high-quality product due to its stiffness, dimensional stability and versatility.

So, what are the advantages of sawing lumber into smaller pieces to glue them together again later? There are 5 main advantages:

- Reliability. During this process the natural imperfections can be spotted and discarded. Otherwise large sections of lumber could hide imperfections inside that affect directly its structural performance (15).

- Unlimited length. Due to finger-joint it is possible to join as many lumber pieces as needed in the longitudinal direction. Therefore, its only limitation would be the requirements of the transport method.

- Highly customizable. As it is made from smaller pieces, they can be curved and modified more easily than larger elements.

- Strength. Gluing of small pieces on their faces allows to obtain a piece with a much larger cross-section that works as a continuous section material.

- Dimensional stability. Glued joints between small pieces limit the individual deformation of these pieces. The assembly has greater dimensional stability against changes in humidity or temperature conditions.

Glulam is suitable either for columns and regular beams, or for long spans. Large spans that can also be managed with glulam arches. Therefore, it could be said it is a highly versatile product.

The development of adhesives not only has improved glulam's performance, but also allowed a wide range of products to develop during the second half of the XX century. Among these products we can find the Oriented Strand Boards (OSB), or the Laminated Veneer Lumber (LVL). However, the product that has had more impact to the spread of engineered timber buildings is Cross Laminated Timber (CLT). Even though, it appeared only 25 years ago in the Austrian university of Graz.

CLT's concept is alike glulam, although in this case the lumber layers are placed with a 90º rotation between each other. This technic provides a planar structural element resistant in both directions. Therefore, this product can be used either horizontally as a slab or vertically as a wall. As a peculiarity, CLT always has an odd number of timber layers as the top and bottom layer must be in the same direction, which establishes the main direction of the structure.

5. PROPERTIES OF ENGINEERED TIMBER

Current technology has granted us a better knowledge and control of timber structure's behaviour, even under a fire. Consequently, its structural reliability has become similar to the levels provided by steel and concrete. But, why should we use timber if we know concrete and steel already work?

5.1. Material properties

The main features required to any structural material are a great strength, σ, a low specific weight, ρ, and a great stiffness, E. The following is a detailed analysis of relationship between them. The "structural scope" of the material, A, is the height at which an unloaded column will fail under its own weight, also called maximum height or insurmountable size (16), is the determining parameter for a material to be appropriate for its use in high-rise structures. It is the maximum height that a one-material element could reach maintaining its section before collapsing by its own weight [1].

[1] $$A = \sigma / \rho$$

Where:

σ: maximum (or admissible) tension of the material.
ρ: specific weight of the material

The Table 2 represents the structural scope of materials commonly used in civil and building structures: regular steel S-275 and high strength steel S-460; four kinds of concrete: light, HLE-25, reinforced, HA-25, High strength, HAR-60, and the concrete used for the new World Trade Centre tower in New York, HAR-95 (17), which is even stronger than the concrete used for the Burj Khalifa, today's tallest skyscraper. Last but not least, two of the most common timber products accepted by the Spanish building code, sawn timber C24 and glulam GL32h.

Timber products (GL32h and C24) have similar structural scope to steel products (S460 and S275). Both materials have the highest structural scope, overcoming even the highest strength concretes (HAR-95). As far as deformation, the basic parameter that relates stiffness, E, and strength, σ, as unitary deformation is ε= σ/E, (Table 2), there isn't much difference between any of these structural materials. In the relation between stiffness and weight (E/ρ), timber doesn't stand out among steel but among the concrete it does.

Concerning seismic actions, which are proportional to weight, as the overall weight is reduced the actions do the same. Besides, the property of recovering its initial shape after being deformed reduce the repair costs after the earthquake. This has been the aim of several tests and researches in CLT structures that proved the stiffness and stability of this timber product against horizontal actions (15). It is noteworthy the seismic table tests where a 7-storey CLT building passed the equivalent of the Kobe 1995 earthquake that reached 7.2

Table 2. Values of structural scope, maximum length, of structural materials.

Material	ρ	E	σ	ε		A
				σ/E	E/ρ	σ/ρ
	kN/m³	kN/cm²	kN/cm²	‰	m	m
S-275	78,7	21000	26	0.8	2,67 e+06	3328
S-460	78,7	21000	43.8	1.4	2,67 e+06	5567
HLE-25	18,0	2210	1.7	0.5	1,23 e+06	926
HA-25	25,0	2500	1.7	0.4	1,00 e+06	667
HAR-60	25,0	3300	4.0	0.8	1,32 e+06	1600
HAR-95	25,0	4000	6.3	1.1	1,60 e+06	2533
C24	4,2	800	1.5	1.4	1,90 e+06	3663
GL32h	4,5	1100	1.9	1.3	2,44 e+06	4131

in the Richter's scale and an acceleration between 0.8 and 1.2 m/s^2 without barely any deformation remaining (18).

5.2. Fire resistance

The main reason that has biased our reaction to timber for structural purposes is its behaviour when exposed to a fire. However, these mass-timber products are extremely hard to set on fire and once they do the behave predictably. In a fire, the outer layers of the wood burn and chars. The charred layers lose their structural capacity but isolates the rest of the wood from the fire due to a low heat transfer coefficient (Figure 3). This coefficient in regular timber is λ = 0.14 W/m·ºK, and when it chars it is reduced to λ = 0.03 W/m·ºK. (19).

Besides conductivity, the main factors that affect timber combustion are: its specie (Softwood burns more easily due to resins and flammable oils contained inside it), its density (lighter woods are more porous and therefore burn faster), its sizing (larger timber pieces have more volume to heat which delays their flash point), its shape (slanted surfaces favour ignition), and its moisture content (the higher it is the slower it burns).

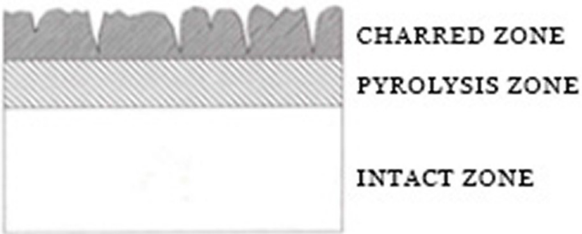

Figure 3. Alterations of exposed to fire timber (19).

The charring speed of the fire-exposed surfaces is between 0.55 and 0.80 mm/min, although it might variate between wood species. This speed is used to calculate how much extra material is needed to prevent the structure from collapsing during the fire.

The main strategy to improve the fire resistance of the timber structural members is to increase the section dimensions in accordance with the extra time required. Another option is to cover the structure with gypsum or other fire-retardant materials. The last option would be intumescent paint, but it isn't very developed for timber (19).

The accidental fire hypothesis (20, 21) establishes security and simultaneity coefficients that imply a reduction coefficient around 0.65 in conventional buildings. This means it isn't always necessary to oversize the structure.

The Eurocode 5 considers different methods. The simplified, the charring method, which is also reflected in the Spanish code (20) is the most common. Whereas the reduced strength and the advanced method are used lees often.

Another strategy against fire is the encapsulation method. This method hides and protects the timber structure with fire-retardant materials like gypsum. Furthermore, timber isn't a conductive material as steel is (Figure 4). This avoids the spread of the high temperatures to more vulnerable parts of the global structure far away from the fire that might be bearing greater loads.

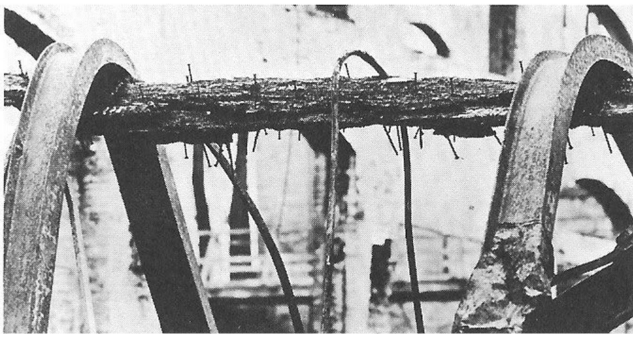

Figure 4. Timber beam holding 2 IPEs melted after the San Francisso's earthquake in 1906 (22).

Joints are the weakest spots during a fire. Charring depths are deeper due to the joint design or because of the use of steel connectors that carry the heat to the core of the junction. Therefore, steel connector must be hidden inside the timber and protected by it.

5.3. Eco-friendly material

In recent decades there has been a rediscovery of timber, especially in industrialized countries, where contemporary awareness advocates the need to protect natural resources. The large amounts of energy and high greenhouse gas emissions needed to produce high-tech building materials, such as steel or concrete, are incompatible with this growing concept of environmental sustainability.

In this sense, wood constitutes the supporting structure of the tree and has the advantage of being a structural product at source, without the need for an industrial transformation process associated with the high energy cost that this entails. Once a tree dies, the CO_2 absorbed during its life starts returning into the atmosphere as the tree decays. However, the wood elements placed on site fix the carbon captured in their cell walls throughout the useful life of the structure, contributing to a fully sustainable development. In addition, the use of wood certified with FSC, PEFC, etc. seals, which guarantee that wood comes from sustainably managed forests, contributes to increasing the rate of atmospheric CO_2 fixation. Sustainable management ensures that volume of cut wood is below the production capacity of forest mass and the regeneration of all felled trees. During their growth, new trees are able to fix a much higher amount of CO_2 than previous adult trees, because their photosynthetic activity is more intense.

After the wood elements have been used once, they can be reused in other buildings, recycled for other uses, and even burned or left to decompose in landfills, in which case the stored CO_2 is returned to the atmosphere. Therefore, the longer the life of wood elements, the greater the benefit to the environment.

It is estimated that production of one cubic meter of timber is able to absorbe between 1 and 1.6 tons of CO_2 (24). According to Green (23) a 20-storey building with a timber structure could store 3150 tons of CO_2. If the same building had a concrete structure it would generate 1215 tons. Therefore, the difference of material implies 4365 tons of CO_2 in our atmosphere, the equivalent of 900 cars off the road for a year. Steel and concrete, in comparison to timber, require 26% and 57% more energy, release 34% and 81% more greenhouse gases, generate 24% and 47% more pollutants into the air, unload 400% and 3000% more pollutants into the water, produce 8% and 23% more solid waste and use 11% and 81% more resources (percentages obtained regarding the weight of material used).

The ecological advantages of timber aren't limited to the production and construction phase. Timber also helps to the overall energy efficiency of the building as insulation. Timber has a heat transfer coefficient (0.14 W/m·K) 14 times better than concrete (2 W/m·K) and 350 times better than steel (50 W/m·K) As a matter of fact, it's only 4.5 times less insulating than medium density rock wool (0.04 W/m·K), one of the most common insulating materials (25).

5.4. Construction process

As any prefabricated product, engineered timber involves a reduction of time in the construction process, which reduces costs. After timber layers are glued together, the material is cut precisely with computer numerical controlled (CNC) machines. This way the pieces can be placed and joined easily during construction. These ready-to-place products allow a just-in-time delivery method, which avoids the need of on-site storage, as products are delivered the same day they are needed. It also reduces the waste produced on site and the waste produced on the workshop can be recycled into other products.

To set a couple examples, the Stadthaus had a construction pace of 1 floor per week (26). While the Bridport House only took 12 weeks, 4 workers and 1 supervisor to build an 8-storey apartment building (15). None of these 4 workers were specialised in CLT nor timber construction as these products use very simple construction methods. In short, these prefabrication methods reduce cost and time during construction, nevertheless, they require extra time in the design process.

6. STRUCTURAL ANALISIS: SLENDERNESS

From a structural point of view, a high-rise is a building where horizontal forces prevail over vertical forces, which have a direct impact on the structural design. Therefore, not every tall building can be considered a high-rise, only the ones slender enough to not be able to dissipate the horizontal forces through a wide base.

Slenderness, λ (relation between height, H, and base dimension, B), is an essential structural parameter in high rises. We try to obtain the slenderness limit for any height.

6.1. Slenderness by stability

Regarding stability, the maximum slenderness is obtained from checking for horizontal displacement due to the gravitational forces, P, whose effect is stabilizing, and the horizontal forces, W, whose effect is destabilizing (Figure 5) [2].

[2] $$\frac{P}{W} \geq \frac{H}{\beta \cdot B}\ ;\ \frac{\gamma_p \alpha \rho ABH}{\gamma_W WAH} \geq \frac{H}{\beta \cdot B}$$

Where:

P Gravitational forces.
W Horizontal force, wind.
H Total height of the building.
A Base dimension of the building's fraction stabilized by the bracing element in the perpendicular direction to the wind action.
B Base dimension of the building in the wind's direction.
β Fraction's depth of the bracing, resistant to the wind.
α Fraction's weight that contributes to stability.
ρ Specific weight of the building.
γ_p Security coefficient towards stabilizing forces (favourable effect). This includes the effects of code values for partial coefficients and the combination of permanent and variable loads.
γ_w Security coefficient towards destabilizing forces. (unfavourable effect).

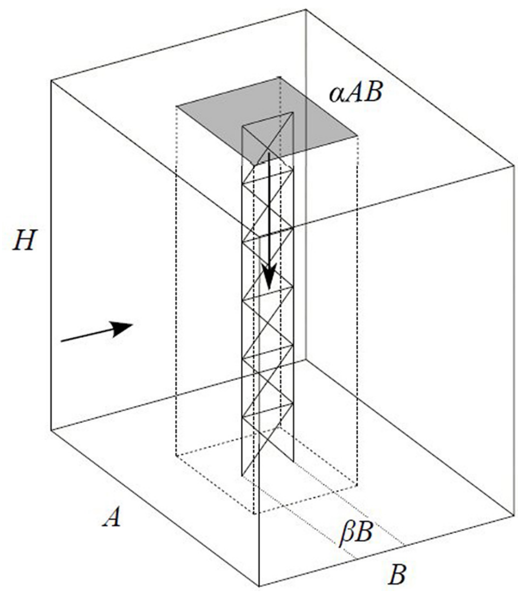

Figure 5. High-rise unit, a bracing element and its tributary volume.

Solving for H/B [3]. By substituting with construction conventional values, and as stability improves as the weight fraction that reaches the bracing element increases, we can state that for a greater fraction area, α, and a greater fraction depth, β, to obtain the slenderness limit the greater value of both features is used [4].

[3] $$\lambda = \frac{H}{B} \leq \alpha\beta \frac{\gamma_p}{\gamma_W} \frac{\rho}{W} B$$

[4] $$\lambda = 1 \cdot 1 \frac{0.7}{1.5} \frac{2.3}{1} B = B$$

Therefore, maximum slenderness by stability is proportional to the base dimension in the direction of the wind and thus the tallest buildings can also be the slenderest. However, as height increases, the following method can be more restraining.

6.2. Slenderness by deformation

The horizontal displacement at the top its linked to its slenderness. Horizontal actions cause a horizontal movement on the top of the building. The Spanish building code (CTE) (27) limits the displacement, δ, to 1/500 of its total height, H. Therefore, the maximum slenderness depends on the unitary deformation, ε. In the vertical elements, or supports, part of this deformation is due to the shortening under compression.

The rest will be an increment by compression or tensile stress produced by the wind. Oscillations and aerodynamic effects are not considered.

To obtain the unitary deformation due to the wind from the total deformation a section of the bracing is analysed (Figure 6). Both ends are compressed due to the gravitational forces. However, while one end is compressed the other end is decompressed due to the wind forces.

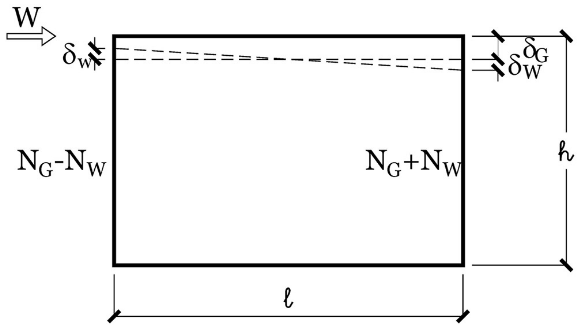

Figure 6. Deformations and internal forces of a section of a bracing.

In the decompressed end (left side on the Figure 6), the axil value of decompression due to the wind (unfavourable effect), N_{Wdlim}, can't be higher than the compression axial generated by the favourable effect, N_{Gf}. Al most, they can be equal, so that the support does'nt reach a tensile stress, and don't pass the tensile stress on to the foundations [5].

[5] $$N_{Gf}-N_{Wdlim} \geq 0;\ N_{Wdlim} = N_{Gf}$$

[6] $$N_{máx} = N_{Gd} + N_{Wdlim}$$

The maximum axial stress to design the compressed end, $N_{máx,}$ will be the sum of gravitational forces, N_{Gd}, and wind forces, N_{Wdlim}, both as an unfavourable effect[6]. The relation between axial forces due to gravity considered as favourable [7] and unfavourable [8] is stablished trough a proportional factor, Φ [9]. Solving and substituting for standard values [10]. For the following calculations we use the value Φ = 0.3.

[7] $$N_{Gf} = G \cdot \gamma_{Gf} + Q \cdot \gamma_{Qf}$$

[8] $$N_{Gd} = G \cdot \gamma_{Gd} + Q \cdot \gamma_{Qd}$$

[9] $$N_{Gf} = \Phi \cdot N_{Gd}$$

[10] $$\Phi = N_{Gf} / N_{Gd} = (G \cdot \gamma_{Gf} + Q \cdot \gamma_{Qf}) / (G \cdot \gamma_{Gd} + Q \cdot \gamma_{Qd}) = 0.3$$

Where:

G Permanent loads.
Q Variable loads.
γ_{Gf} Security coefficient for the favourable effect of permanent loads.
γ_{Qf} Security coefficient for the favourable effect of variable loads.
γ_{Gd} Security coefficient for the unfavourable effect of permanent loads.
γ_{Qd} Security coefficient for the unfavourable effect of variable loads.
Φ Proportional factor between favourable and unfavourable axial's effects.

The relation between maximum deformation due to the wind loads, $\varepsilon_{Wmáx}$, and the maximum deformation due to all effects considered, $\varepsilon_{máx,}$ on a linear elastic behaviour will be the same as the one produced by its axial forces, $N_{Wdmáx}$ and $N_{máx}$ [11][12]. On the limit, the maximum wind stress at the base N_{Wdmax} can't surpass the limit N_{Wdlim} imposed so there aren't decompressions that lead to tension stresses on the foundations [13]. Thus, the unitary deformation due to the wind is at most around 30% of the maximum unitary deformation $\varepsilon_{máx}$ [14].

[11] $$\varepsilon_{Wmáx} / \varepsilon_{máx} = N_{Wdmáx} / N_{máx}$$

[12] $$\varepsilon_{Wmáx} / \varepsilon_{máx} = N_{Wdmáx} / (N_{Gd} + N_{Wdmáx})$$

[13] $$\varepsilon_{Wmáx} / \varepsilon_{máx} = 1/(1 + N_{Gd}/N_{Wdlim}) = 1/(1 + N_{Gd}/N_{Gf}) = 1/(1 + 1/\Phi) = 0.3$$

[14] $$\varepsilon_{Wmáx} = 0.30\ \varepsilon_{máx}$$

[15] $$\frac{\delta}{H} = \frac{\varepsilon \cdot H}{2 \cdot B} < \frac{1}{500}$$

[16] $$\lambda = \frac{H}{B} \rightarrow \lambda_{aprox} = \frac{2}{500 \cdot \varepsilon_{Wmax}}$$

Hereunder, we consider two methods. The first approximates the overall behaviour under wind actions considering the building as a solid core cantilever and constant cross-section area (c.c.s.). The outcome of this method will be higher slenderness than reality as a building will never have the stiffness of a solid core beam, even with structural walls, and the cross-section won't be the same all the way to the top. The deformation on top, δ, is linked to the height of the building [15], solving for the slenderness we can obtain [16]. The results are shown on the second last column of Table 3.

Table 3. Maximum slenderness by structural material.

Material	**Stiffness**	**Strength**	**Security**	**Strength**	**$e_{w,max}$**	**λ_{aprox} c.c.s.**	**λ s.c.s.**
	E	**fk**	**γ_M**	**$f_{trabajo} = \frac{f_k}{\gamma_M \cdot \gamma_P}$**	**30%·$e_{máx}$**	**2/(500ε)**	**3/2(500ε)**
	kN/cm²	**kN/cm²**		**kN/cm²**	**‰**	**-**	**-**
S-275	21000	27,5	1,05	17,5	0,25	**16**	**12**
S-460	21000	46,0	1,05	29,2	0,42	**10**	**7**
HLE-25	2210	2,5	1,5	1,1	0,15	**27**	**20**
HA-25	2500	2,5	1,5	1,1	0,13	**30**	**23**
HAR-60	3300	6,0	1,5	2,7	0,24	**17**	**12**
HAR-95	4000	9,5	1,5	4,2	0,32	**13**	**10**
C24	740	2,4	1,6	1,0	0,41	**10**	**7**
GL32h	1100	2,9	1,56	1,2	0,34	**12**	**9**

The second method is more precise, the bracing component is considered as a strict cross-section area (s.c.s.). Attending to the deformation of the supports as cantilever's chords, that are shortened due to gravitational loads, and later, due to the wind, one end is shortened, and the other is decompressed (Figure 6). The accumulated shift between 2 floors, θ, of a height, and a span, l, due to the shortening of both ends [17] and by unit of length, h, the curvature can be obtained [18].

[17] $$\theta = \frac{2\cdot \delta_w}{l}$$

[18] $$c = \frac{2\cdot \varepsilon_w(\mathrm{h})}{l}$$

The displacement is the second integral of the curvature in all its height [19]. In order to ease the calculations in an non-dimensional form, it is multiplied and divided by H and $\varepsilon_{Wmáx}$. [20]. To ease the integral calculus, it is solved [21], where z is a dimensionless height [22].

[19] $$\delta = \int_0^H \theta(h)dh = \int_0^H dh\int_0^h c\ dh = \int_0^H dh\int_0^h \frac{2\cdot\varepsilon_w(h)}{l}dh$$

[20] $$\delta = \int_0^H \frac{H}{H}dh\int_0^h \frac{2\cdot\varepsilon_{wmáx}\cdot H\cdot\varepsilon_w(h)}{l\cdot\varepsilon_{wmáx}}\frac{dh}{H}$$

[21] $$z = \frac{h}{H} \quad \text{and} \quad dz = \frac{dh}{H}$$

[22] $$\frac{\delta}{H} = 2\cdot\varepsilon_{wmáx}\cdot\lambda\cdot\int_0^1 dz\int_0^z \frac{\varepsilon_w(h)}{\varepsilon_{wmáx}}dz$$

Approximately, the unitary deformation law is the equation of a straight line between 0 and 1 [23]. Solving the integral [24] and then solving for the slenderness [25].

[23] $$\frac{\varepsilon_w(h)}{\varepsilon_{wmáx}} = 1 - z$$

[24] $$\frac{\delta}{H} = 2\cdot\varepsilon_{wmáx}\cdot\lambda\cdot\frac{1}{3}$$

[25] $$\lambda = \frac{3}{2\cdot 500\cdot\varepsilon_{Wmax}}$$

Table 3 compares the maximum slenderness of different structural materials. These factors will be between both values, λ_{aprox} (with a constant cross-section) y λ (strict cross-section).

In order to build slenderer high-rises, we must use materials with less deformations, although the structure can always be oversized to reduce it, but this is not usual. Table 3 shows that all the materials studied have a similar slenderness limit, except for 2 types of concrete, HLE-25 and HA-25, which make it possible to achieve a constructive slenderness of the order of double or even triple with respect to the rest of materials. Timber doesn't seem to stand out, but the slenderness obtained are within usual construction values. To increase this slenderness in timber construction, one of the strategies is to use concrete cores as shown below.

It must be borne in mind that the study carried out is a theoretical analysis in which a linear-elastic behaviour of materials has been considered, which does not include joints between elements or the possible combination of materials. However, despite the theoretical nature of the study, it is very useful to compare materials with each other and understand the limit imposed by the slenderness in each of them.

7. STRATEGIES AGAINST HORIZONTAL LOADS

It is interesting to analyse the three most common strategies to solve the problem of horizontal loads, mainly wind and seismic loads. (Figure 7).

The first and the most conservative strategy is based on maintaining one or more vertical cores made of concrete. These concrete cores usually host the stairs and elevator shafts. The rest of the structure follows a traditional layout of pillars and CLT floors. The CLT slabs work as rigid diaphragms that transmits the horizontal loads to the concrete cores. Therefore, these buildings possess the timber advantages, lighter structure, low CO_2 emissions and reduced times during construction; but also takes advantage of concrete's low deformability. The Brock Commons, in Vancouver, or the HoHo, in Vienna, are two of the buildings that are currently using this strategy.

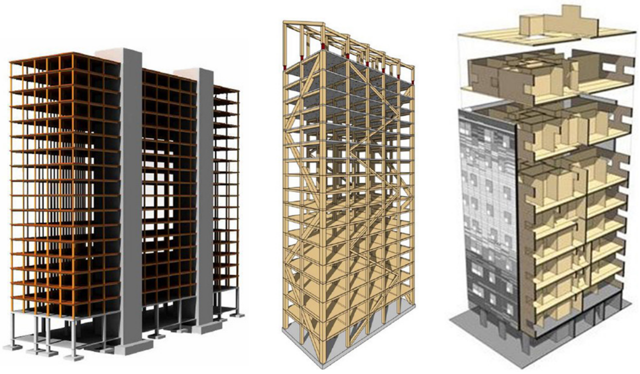

Figure 7. Three strategies against horizontal loads: Concrete Cores from Brock Commons (32), Bracing from Mjostarnet (85.4 m) (34) y CLT panels as bearing walls from Stadthaus (30 m) by Waugh Thistleton Architects.

In the second strategy, diagonal Glulam beams (or steel when smaller sections are needed) brace the building. The only thing innovative of this strategy is the material used, as it is the same used by other skyscrapers such as the John Hancock tower in Chicago. This method implies a special attention to the connections in tension stress as they can be weak points. This alternative requires greater dimensions for the main structure compared to the first strategy. However, it avoids the use of other materials, maximizing the benefits of timber construction. This strategy was first used by the Treet reaching 53 meters-in-height and later by the Mjostarnet reaching 85.4 m (Figure 10).

The last strategy is based on CLT. The CLT panels are used as both, shear walls and slabs. These CLT elements are disposed in both directions on plan to assure its resistance to horizontal loads in any direction. This leads to a structure completely made of timber. However, this strategy is more suitable for less slender buildings and buildings without open floor plans. Therefore, this strategy is commonly used by residential mid-rises such as the Stadthaus from London.

8. TIMBER HIGH RISES

8.1. Pioneers and its progress on height

In the past 10 years the number of architects interested on the timber properties to create light, resistant and environmentally friendly buildings have increased significantly. In order to be able to build one, these architects often need a reformulation of their country's construction code, usually too conservative towards timber. For example, in Germany, until 2002 timber structure buildings could only reach a height of 3-floors. And even 6 years after Germany's code was modified, the 7-storey E3 building from Berlin), whose structure is made of mass timber, was required to build a concrete emergency staircase detached from the building (28).

These buildings, pioneers, have paved the way for new timber constructions. The technology has been available for years; however, the problem is the scepticism towards this material. In 2008, there was only one timber building that surpassed the 8-storey limit. In June 2017 there were already 40 buildings constructed, in construction or planned (9).

The Stadthaus from London (Figure 8), was built in 2009 reaching a height of 30,3 m and 9 storeys. It stands out for showing the feasibility of timber structures made of CLT and Glulam as well as its technological and economic competitiveness compared to steel and concrete. It creates a pattern, highly repeated afterwards, the use of CLT panels as vertical structure (walls) as well as horizontal structure (slabs) on top of a concrete 1-storey podium that accommodates the ground floor (29).

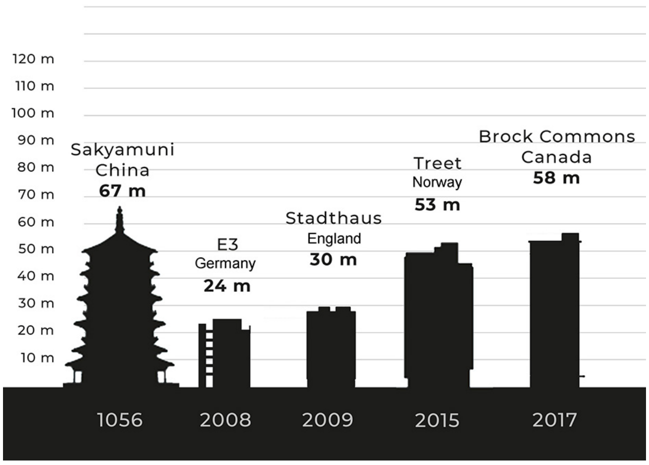

Figure 8. Pioneer buildings, new contemporary heights compared to the ancient Sakyamuni pagoda.

In 2015 with the construction of The Treet in Norway (Figure 8) the symbolic height of 50 meters is finally surpassed. Constructed by BOB BBL, it is conceived as a pilot project to show the feasibility of creating apartment buildings following the *Passivhaus* standards using a prefabrication method (30). Even though the original costs are higher than a conventional concrete structure building, the prefabrication of both, the Glulam main structure and the apartment CLT modules, lead to a reduction in construction times that lead to a reduction of the overall cost of the building. Once again, the timber structure lies on top of a concrete base, although this time instead of the ground floor is the basement. The building incorporates glulam bracing beams. This glulam structure can be seen from the inside and from the outside although it is protected by a curtain wall. The main load bearing structure is designed to receive the apartment modules as if they were «drawers» (31). The building includes concrete floors to increase its weight and reduce the sway produced by heavy winds.

In 2017 the Brock Commons Tallwood House Student Residence (Figure 9) set a new height record: 57.9 meters. Its construction took advantage of the control of the British Columbia University over the building code that affects the buildings within its campus (32). The bearing structure is made of CLT and Glulam pillars and 2 concrete vertical cores. A wooden structure that like the Stadthaus stands on a 1 story concrete base.

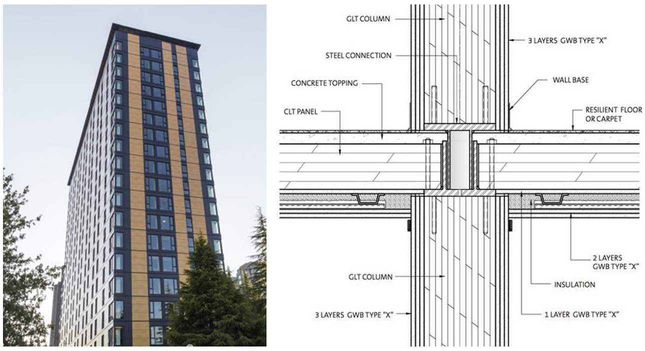

Figure 9. Brock Commons and a detail of the steel conector (32, 33).

Even though the main reasons for choosing timber over concrete or steel might be the carbon sequestration and its innovative character, Acton Ostry suggests that by increasing the time during the design phase using BIM technology to define every detail and enhancing its prefabrication led to a reduction in the overall cost of the building. They designed a steel connector (Figure 9 right) to pass the loads on between pillars in consecutive storeys. It also helps the assembly of the building which cut construction times significantly by 2 to 3 months (33) In order to manage fire resistance required (120 minutes) the structure was covered by gypsum panel, which sadly, hide away the true materiality of the structure. The two concrete cores give the building better stability against horizontal actions (33).

While only a few buildings dare to surpass the heights of their predecessors, many others are being built to already stablished heights (Table 4).

Table 4. Completed timber structure tall buildings (7, 9).

Height	Building	Country	Use	Year
57.9 m	Brock Commons	Canada	Residential	2017
52.8 m	Treet	Norway	Residential	2015
45 m	Carbon 12	USA	Residential	2017
40.9 m	Origine	Canada	Residential	2017
33 m	Dalston Lane	United Kingdom	Residential	2017
32.3 m	Forte	Australia	Residential	2013
31 m	Lagerhuset	Sweden	Residential	2008
31 m	Trafalgar Place	United Kingdom	Residential	2015
31 m	The Cube	United Kingdom	Residential	2015
30.3 m	Stadthaus	United Kingdom	Residential	2009
28 m	Cenni di Cambiamento	Italy	Residential	2013
28 m	Moholt 50/50	Norway	Residential	2017
26 m	Arbora	Canada	Residential	2016

8.2. New heights under construction

Timber structures are still looking for new limits. Nowadays, there are several buildings under construction, or ready to start it, that will surpass the height limits already stablished (Figure 10), such as the Haut in the Netherlands or the Terrace House in Canada. However, two of them stand among these buildings: the Mjostarnet in Norway and the Hoho in Austria. Both will reach heights over 85.4 meters and are set to be completed along 2019, which will clear the way for future buildings.

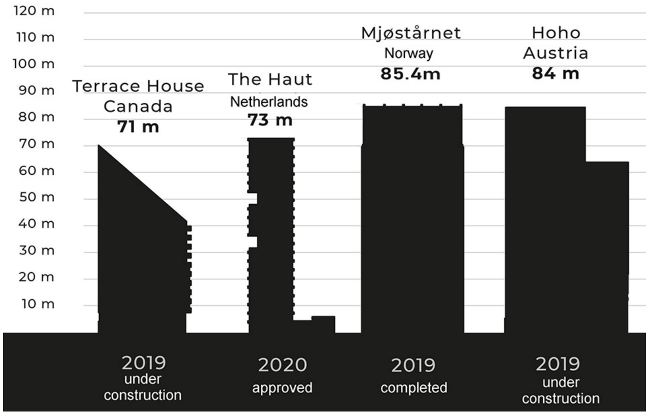

Figure 10. Buildings under construction.

Mjostarnet (Figure 10) follows the typology set by the Treet: a structure completely made of timber with glulam diagonals to brace the building. The ecological aspect of the building is enhanced by the use of local resources. Again, the connectors required special attention as they are the most delicate point of the structure. After several tests from the SWECO company, a steel connector embedded in the glulam beams was decided to be the best solution. The Steel connector is also covered by an intumescent paint layer so the R120 fire resistance could be granted (34).

The HoHo building (Figure 10) has a closer relation with the Brock Commons structure. However, the large size of its concrete core sparked a debate about when a structure stops being considered a timber structure and starts being considered a composite structure. Eventually, the CTBUH decided that at least 85% of the structure needed to be timber, which isn't the case for the HoHo with only a 75% of timber (35).

8.3. A glance into the future

In the past years several architecture firms have stepped in and tried to make their own contributions to this topic. These contributions have been either intensive research that help the evolution of the technique as well as the building codes or speculative projects that show us new typologies and what a building of this characteristics could look like. As many of these projects aren't intended to be built, they are freed from following the most restrictive code issues and from waiting for a developer willing to innovate to invest his money.

One of the most complete research among the industry is Michael Green's work (23), where he approaches technical, economic and social issues. In this paper he also proposes a feasible timber structure for 12 to 20-storey buildings and a construction process called FFTT (Figure 11). The FFTT solution is a tilt-up system of large CLT panels that compose the main load-bearing components of the building, an inner core, the external walls and the floors between both. The large size panels allow to assemble up to 6 floors at a time, which reduces erection costs. The FFTT solution proves that timber buildings can also be cost competitive.

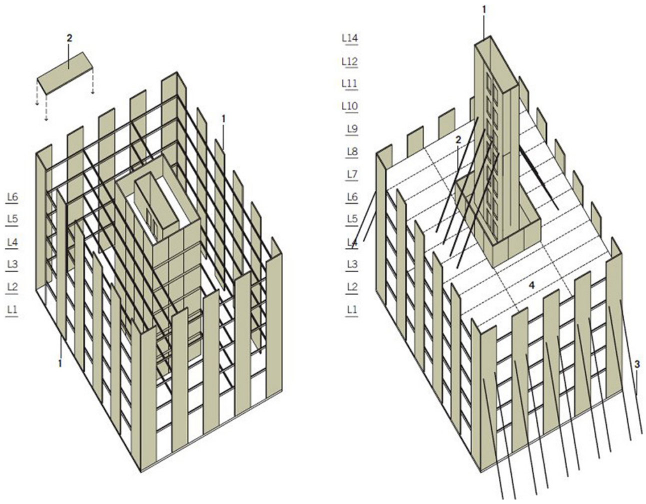

Figure 11. FFTT solution proposed by Michael Green Architects (23).

SOM, a practice specialised in skyscrapers (Willis tower and Burj Khalifa among others), is also researching this topic (36, 37, 38, 39). They state that composite structures (timber-concrete or timber-steel-concrete) (Figure 12) where timber is the main material could reduce the building's footprint around 60% to 75%. Even though an only-timber structure might reduce even more the building's footprint, they consider that it's not worth the high costs and technical complexities. Therefore, for the moment, they opt for composite structures and continue testing different technics.

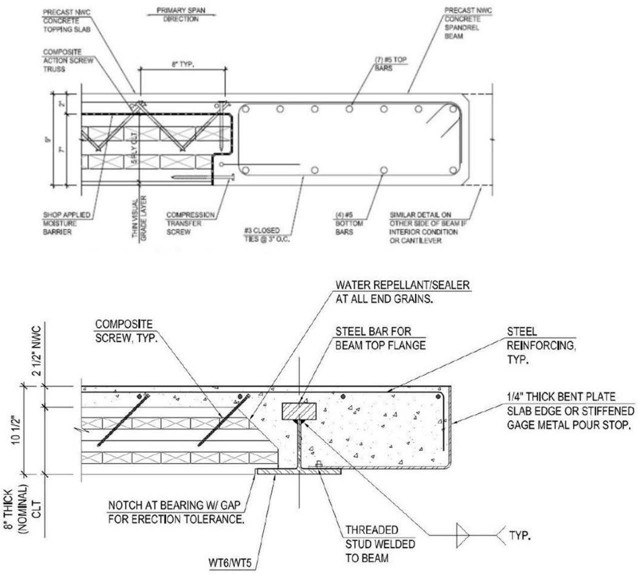

Figure 12. Two concrete-steel-timber composite solutions (38, 39).

Perkins & Will and the consultant Thorton Tomassetti proposed the River Beech project (Figure 13) as part of the urban planning of Chicago's riverfront. The building is composed by 2 slender volumes, built by modules with a structural diagrid, connected by glulam diagonals creating community spaces between them. However, the project is on hold until Chicago's building code is redeveloped (7).

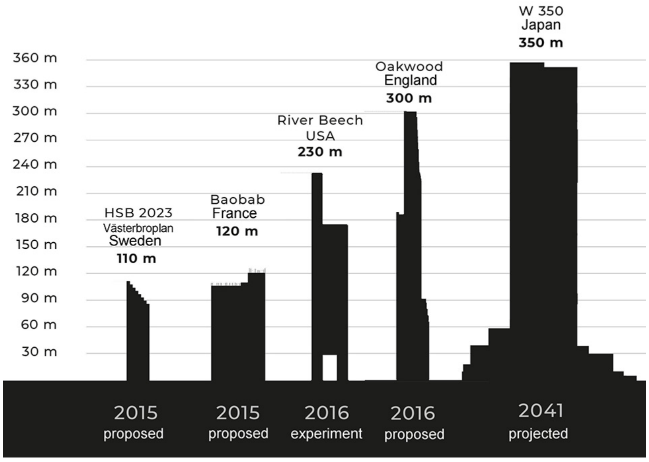

Figure 13. Vissions of the future.

In order to attract the general public many architecture studios, real estate developers and timber companies are producing model projects to show timber benefits. Therefore, the aim of these projects is to eradicate the bias that might be against timber, grow its acceptance and, consequently, speed the evolution of building codes. From an architectural point of view, these projects also help to develop new typologies inherent to wood instead of copying the steel and concrete typologies. The Oakwood tower or the Baobab are two fine examples of these proposals.

However, there are also proposals that hope to be built but are on hold until the researches, techniques and codes evolve enough. The HSB – Västerbroplan, a 223 meters-high wooden skyscraper scheduled for 2023, or the W350 tower, an ambitious project lead by Sumitomo Forestry that seeks to reach a height of 350 meters before 2041, are two of these projects.

9. CONCLUSIONS

Wood has been one of the most widely used building materials for thousands of years. The human being used nearby elements offered by nature, such as stone or logs, to cover their basic needs for shelter and transportation. The arrival of the industrial revolution during the XVIII and XIX centuries allowed the development of other products such as reinforced concrete and steel which, due to the simplicity of mass production and the ability to cover large spans, were progressively erected as predominant structural materials relegating the use of wood to smaller buildings.

Due to growing social awareness in favour of sustainability and energy efficiency fostered by the effect of global warming, in recent decades there has been a discovery of wood in Western architecture. The use of wood in construction contributes to reducing the concentration of atmospheric CO_2 fundamentally through 2 mechanisms. On the one hand, it acts as a carbon store, since it is fixed as a constituent element of vegetal structures; and on the other hand, it acts as a CO_2 sink when absorbed by trees during their photosynthetic activity. The consumption of certified wood from sustainably managed forests favours the regeneration of the forest masses and greatly increases the absorption rate of atmospheric CO_2.

Besides being an ecological material, the burning behavior of timber structures is completely predictable, reason why it is a highly recommendable material to assure the evacuation of people in situation of fire.

Nowadays, the technological and industrial evolution (outdoor adhesives, new wood-based products such as CLT, 3D design software, numerical control machines, etc.) has allowed the timber construction to reach a degree of prefabrication that allows working competitively and with total quality guarantees. The stages of the productive process of design, machining and assembly of the structure can now be carried out in installations that can be very far from the final location of the structure. Prefabrication increases production yields and avoids possible deterioration of the materials collected on site, excessive assembly times or errors in execution by unqualified personnel. As an estimate, construction times can be reduced at a rate of 2 floors per week.

The mechanical properties (rigidity, strength and specific weight) of different types of steel, concrete and wood have been compared analytically, obtaining that wood and steel have a structural scope similar to each other, and higher than concrete. High-rise buildings have two main structural challenges: the increase of the vertical loads due to its own weight, and the increase of horizontal actions due to wind and earthquakes. Against horizontal actions three main strategies are taken: combining the timber structure with concrete cores, glulam diagonals, or CLT shear walls. Wood is also suitable for seismic areas thanks to the energy dissipation capacity and the lightness of the material, as seismic loads are directly proportional to the weight of the building.

As a new evaluation parameter, the maximum slenderness was calculated considering a theoretical building constructed entirely with each one of these materials, obtaining, in general, that the buildings of wood and steel can reach similar slenderness but inferior to the buildings of concrete.

Initially, the development of timber buildings was limited to countries as UK or Norway, where their codes are less limiting towards timber or more flexible to accept additional safety measures instead. Luckily, its environmental advantages are leading more and more governments to reconsider the laws that regulate timber structures. Other countries, like USA or Canada, go further and are subsidizing researches and constructions that use this material in more than 20-storey buildings. Each day more countries are becoming interested in taking part in this timber revolution. In the battle for height, a timber building has already been built that exceeds 85 metres (Mjostarnet in Norway). Due to the global fight against climate change, we are witnessing the starting point of the use of wood in high-rise building structures, whether it is used alone or in combination with other materials, which must be a driving force for sustainability in XXI century society.

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