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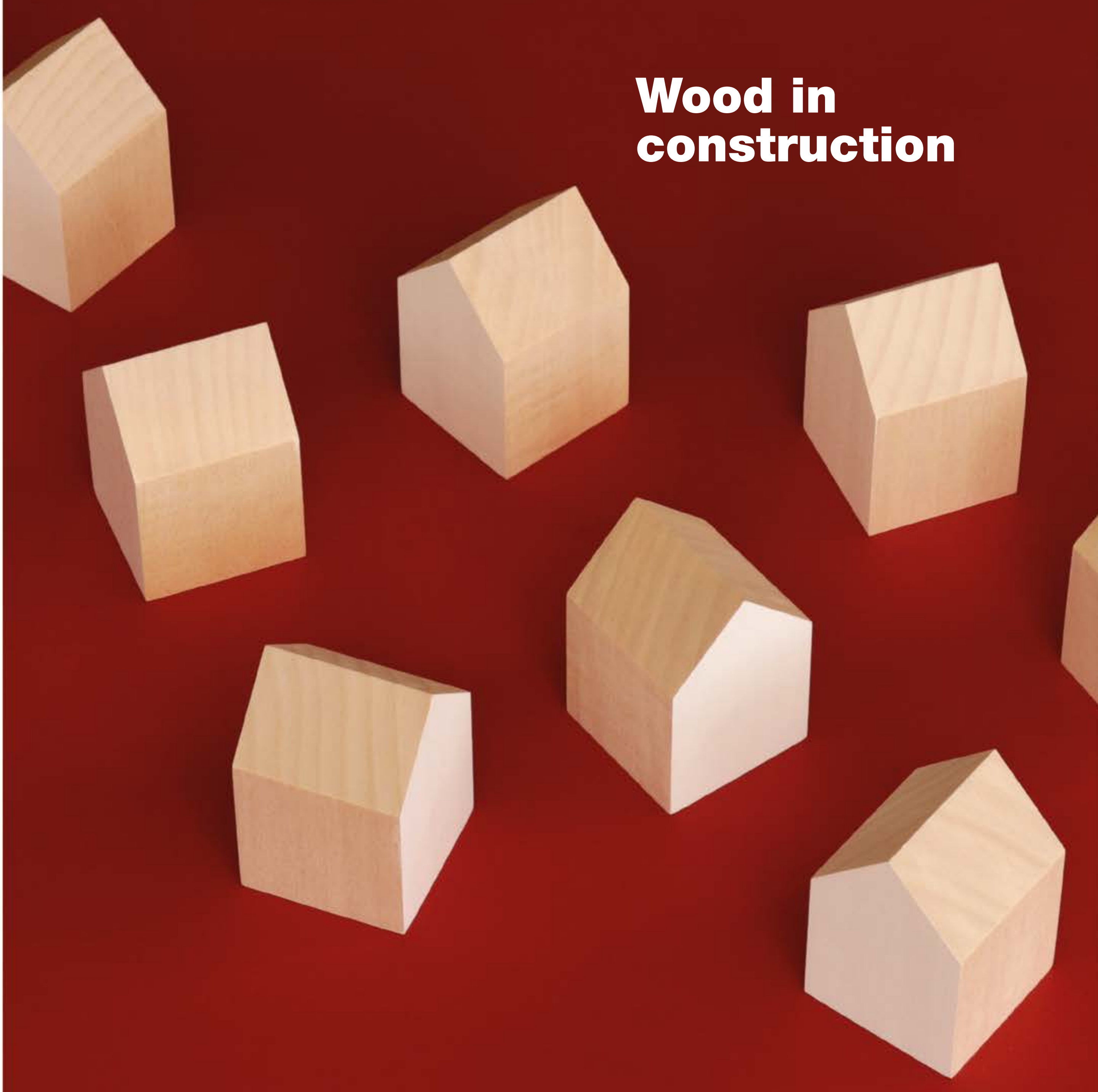
Innovation and knowledge transfer

March 2020

Wood in construction



Generalitat de Catalunya
Departament d'Agricultura, Ramaderia, Pesca i Alimentació

Rural Cat

Oriol Anson Fradera
Director General of Rural Development
Department of Agriculture, Livestock,
Fisheries and Food

The use of value-added wood products promotes certified sustainable forest management

Wood is a material that is all around us in our daily lives without us even realising it. It is a versatile material with a host of possibilities, enjoying a wide range of qualities which means it can be used in a variety of ways from single-use paper to luxury decorations, and sculptural material.

In construction it has been a material used since time immemorial. Along with stone, it was an accessible and local material, easy to work with and easier to transport than other heavier materials. If we look at rural constructions and farmhouses that still retain original elements, we will see that wood is very much present. From the roof to the floors, in the doors and windows and furniture, and in many cases the type of wood can tell us how wealthy the house was when it was built.

During the last century its use in construction has declined in favour of other materials such as concrete and steel. These had a competitive advantage by providing building solutions that solid wood could not, despite being much more expensive to produce and with negative environmental impacts.

The 21st century, however, presents us with new social and environmental paradigms that force us to rethink all areas of engineering, including architecture. Climate change, resource depletion, the end of the linear economy, and its consequences, have made sustainability no longer an option, but an obligation. It is within this context that wood re-emerges as an opportunity and solution. Wood is a renewable and sustainable material, which is produced from the energy provided by the sun. Wood allows CO_2 to be captured from the atmosphere and to be stored in the wood for as long as we are able to use it. It is also an element that provides great comfort and well-being for those who can enjoy a home or furnishings built with wood.

In this new environmental paradigm, forests are also suffering the effects of global change. Sustainable forest management is a tool to ensure their adaptation and to maintain and increase the ecosystem services they provide, including the regular and sustainable supply of raw materials. In Catalonia, 260,000 hectares of forest area are PEFC certified, which ensure sustainable forest management and timber harvesting. The use of value-added wood products is a clear ally in promoting this forest management. Technological advances have also made it possible to make a qualitative leap forward in wood within the construction industry. From a material used directly with a simple sawing processing, it has become part of a wide range of materials, from panels to glulam beams. Wood has gone from being a building material to becoming the raw material for new elements, and this has allowed the draughtsman's imagination and technology to envisage a new future for wood within the construction industry.

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Coordination and production
Maria Josep de Ribot Porta, Imma Malet Prat, Annabel Teixidó Martínez, Ester Blanco Casellas (CTFC/FBS) and Jordi Gené Sera (INCAFUST).

Language correction and advice
Joan Ignasi Elias Cruz and Lluís Piqueres Pla.

Graphics and layout
Carlos Guzman Lorente.

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WOOD.
A material of yesterday and tomorrow

Mas Anfruns. Photo: Miquel Escobar from Bioarkiteco. (http://bioarkiteco.com)

Masia Can Fàbregas del Bosc. Photo: A. Alvarez (CC BY SA)

01. Introduction

We live in a constantly growing world, where society requires more and more new buildings. Cities are growing all the time, and so is the awareness for a more sustainable world.

Today, most buildings are built with the same materials. Concrete and steel are the most common materials used in building structures, both locally, nationally and internationally. However, the use of these materials is starting to be contested due to the high energy consumption and pollution involved in their manufacture, as well as the ecological footprint due to them being non-biodegradable.

Today's society is increasingly aware of the problems posed by climate change. It is exploring and demanding alternatives to mitigate the greenhouse effect. This has led to a growing interest in wooden structures. A material that utilises the material resources that nature offers us.

The wood manufacturing process uses fewer resources than other materials, and produces less greenhouse gases, such as CO_2, than the manufacture of conventional materials.

On the other hand, timber constructions provide light, modular and easy-to-build buildings, like pieces of a puzzle to be put together.

02. Tradition of wood in Catalonia

Catalonia has a long history of timber constructions and it is a well-known structural type, as well as a unique cultural heritage of our construction system. Throughout Catalonia, there are roof and floor structures made with wooden beams that have survived the passage of time, having been used for centuries and well into the 20th century.

In fact, the traditional Catalan farmhouse is the quintessential construction of this traditional system. Based on load-bearing walls of either dry stone, adobe or masonry, topped with wooden beams.

The construction process and the wood used was closely related to the construction area, to the types of accessible forests and to an ageing process over time.

Today, wood is still being used and many structures are made with this material.

03. Wooden structures around the world

Worldwide, the most innovative and cutting-edge wooden structures today are those with CLT (Cross Laminated Timber) panel structures which have changed the landscape of timber construction itself.

Using wood for this type of panel has meant a leap forward on an international scale, from small-scale constructions to high-rise buildings, as a clear response to the growth and sustainability demands of the modern world.

La Canaleta School - Vilaseca. Project by 2260mm arquitectes. Photos: Lluís Bernat (4photos.cat).

IES Serra Noet - Berga. Photo: Bis Structures.

Cavallers Building - Lleida. Photo: Trass arquitectura.

There are buildings of more than 10 storeys built with this system, both in Europe and America.

In Canada, Acton Ostry Architects Inc. designed the 53m high Brock Commons Tallwood House, a residence for Columbia University students. The structure combines vertical concrete cores with CLT panels and laminated timber columns.

The use of cross-laminated timber presents a structural alternative with a long way to go, which has already made the leap to large-scale construction.

Norway has a couple of projects where wood is the key element of the structure. CLT panels are combined with glulam trusses to provide stability against horizontal thrusts due to the wind. The Treet Tower in Bergen is designed by Geir Brekke of Lund and Partner and is 49m high. And the MjØs tower, near Oslo, is the work of Voll Arkitekter, so far the world's tallest wooden building at almost 85m high.

04. Wooden structures in Catalonia

Catalonia is not far behind in the race for wooden structures, especially in CLT combined with glulam elements.

While it is true that the sector is in its infancy, there are already buildings designed and built with this structural type.

Apart from the most common structures of this type, single-family detached homes, we also find this type in extensions and refurbishments, and small auxiliary constructions.

In recent years, however, it has expanded and the first buildings of a certain size are being made with panels. This construction system is increasingly being used in larger buildings.

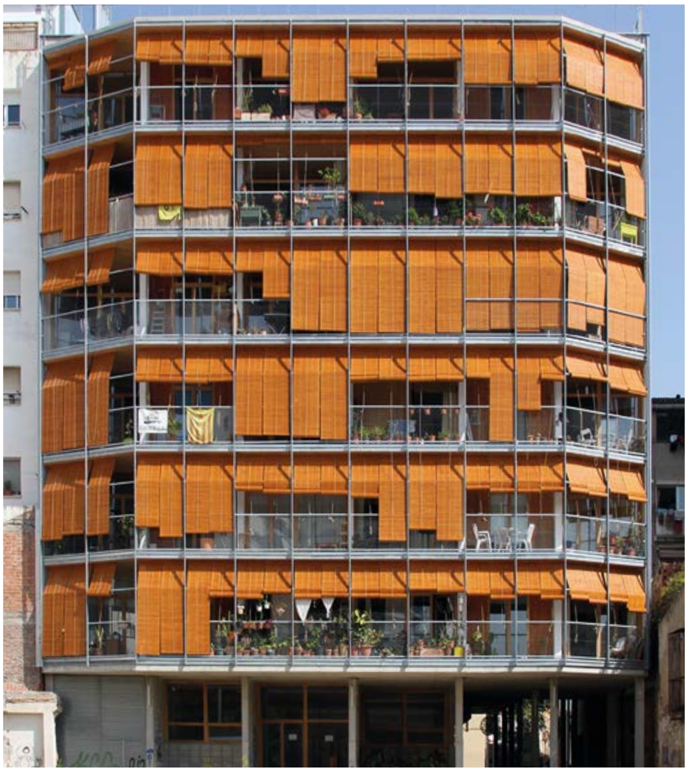
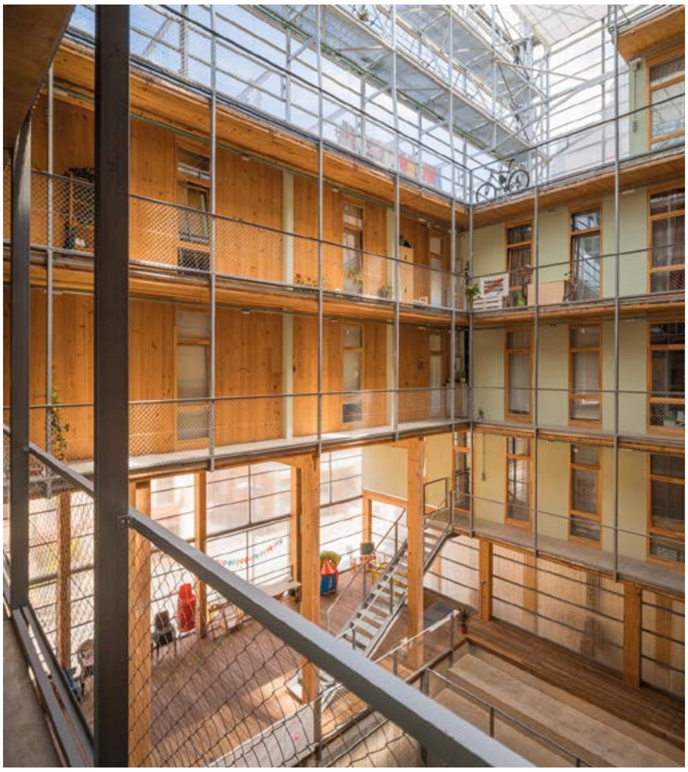
Recently, we have seen this in public education facilities, such as the Serra i Noet Secondary School in Berga, designed by Fabregat & Fabregat Arquitectes and built by Velima Systems in collaboration with KLH (VIAS+Romero Polo). The building has a surface area of around 3,500m² and a height of three storeys. Also, the Canaleta Primary School in Vilaseca, designed by 2260mm Arquitectura and built by Egoin. The school has an area of 3,480m² and a height of two storeys.

The first buildings for residential use are also being built, using glulam structures and CLT panels.

Two major examples currently in Catalonia are the La Borda building in Barcelona, a project by Lacol Arquitectura Cooperativa and built by Egoin. The building has a height of seven storeys and a surface area of 3,000m². The Cavallers building in Lleida, designed by Trass arquitectura and built by Altermateria (Construccions Pallás, SL). It has a height of six storeys and a surface area of 941m².

05. What do wooden structures contribute to construction?

The fact that it is a light and industrialised system allows for reduced build times, minimising the impact of construction work. At the same time, the

Building This is from before the meeting, it was mentioned that it could change. - Barcelona. Photos: Lacol architecture cooperative (left) and Lluc Miralles (right).

waste generated on site is reduced, as all the material arrives directly from the workshop.

And no less important is that, as a natural material, the ecological footprint is low. CO_2 generation is significantly reduced and it provides more sustainable and environmentally friendly buildings.

There are false beliefs about the material that relegate it to last alternatives when choosing the structural type, not realising its great potential as a material. Fire and moisture are the two most common issues that create uncertainty and are completely false. A well-sized and well-treated structure will provide the same performance as with any other material, guaranteeing its stability and integrity at all times.

Wood in the form of CLT panels, which are becoming increasingly popular, brings a new vision to both structure and architecture, two closely interconnected disciplines. In Catalonia, this is still an unlikely option for two main reasons. Firstly, the ever-increasing scale of the buildings being built makes it absolutely necessary to have specialised structural consultants to carry out the design and control of the construction. These consultants can provide objectivity as they are not associated with any specific company and can offer comprehensive advice and an overview, not only about wood. And secondly, even though Catalonia has natural resources, they are generally underutilised. This system does not mean a local product, but most constructions are made with wood from northern Spain and abroad.

On the other hand, it is important to bear in mind that there are currently few well-qualified professionals in implementing this structural/construction system. Key construction aspects must be carefully considered in this system, such as the joints, which are taken for granted in other structural types. Therefore, there is much to learn in this sector and innovation must always be one step ahead.

Care must also be taken not to overuse the material according to the resources of each location, in order to prevent excessive deforestation from occurring in the future.

Wooden structures have come a long way, but they still have a long way to go.

Author

Ariadna Grau Llinares
Project manager.
BIS structures.
agrau@bisstructures.com

Esther Muñoz Gavilán
Team Leader.
BIS Structures.
estherm@bisstructures.com

David Garcia Carrera
Founding Partner and Technical Director.
BIS structures.
davidg@bisstructures.com

HISTORICAL OVERVIEW
of the technological evolution of timber construction systems

Log house (Norsk Folkemuseum, Oslo). Photo: Eduard Correal Mòdol. INCAFUST.

Timber construction systems have evolved over time in tandem with technical knowledge, the emergence of new materials, available tools and various social and legislative changes. Each system offers advantages and limitations particular to the stage of technological development of the period in which they emerged. Not surprisingly, the older and simpler systems have the advantage of requiring very few additional aids, while the more modern and sophisticated ones, despite being more optimised, require a powerful industry behind them to make them feasible. Broadly speaking, there are eight constructional types of wooden buildings: primitive cabins, log hous-

Wood has such a strong capacity that it even supports the huge technological leap between log cabins and CLT skyscrapers.

es, heavy frame buildings, reinforced timber frame buildings, light balloon frame buildings, light platform frame buildings, cross-laminated timber panel buildings and, finally, a fairly extensive type of complex constructions incorporating large-scale elements such as domes and large structures.

01. Chronology of construction systems

Cabins is the most primitive construction system, which uses almost unprocessed natural materials. These come from the immediate environment, requires a very low amount of energy and is therefore the system with the lowest environmental impact. It can be said that it is a completely circular and truly zero kilometre construction, although it only covers the most basic needs of shelter and security for its inhabitants. On the other hand, the constructions are ephemeral if they do not receive constant maintenance, comfort and performance are very basic, with ground-floor constructions and a very small size. The constructive elements used are those provided by nature and, for example, the light of the beams will depend on the length of the trunks or branches.

The materials and solutions adopted by the various construction systems are a reflection of the technological development and the resources available at each period and place.

A factor to be taken into account in the evolution of construction systems is the amount of effort required to build a house. When resources are very limited it is not possible to resort to faraway or heavy materials. In fact, this pattern can be clearly seen in traditional architecture. The geology of the land determines the type of stone used in the walls and where there is no stone but clay, the houses tend to be adobe. The same happens with the roofs: if there is clay we will find Arab-type roof tiles, or in other areas these roof elements are made of slate or wood.

Log houses, also known as Canadian houses, are the most evolved log cabins. This ancestral system was widely used up until the 1920s in remote areas and generally where sawn wood was unavailable. The size of the buildings are completely determined by the length and diameter of the logs. In the more rustic finishes the logs are not machined. However, nowadays it is common to see the logs rounded mechanically to provide easy assembly and higher quality finishes. In the same vein, the logs were traditionally fitted together using an axe, but nowadays numerical lathes can be used. This is a rough and relatively heavy construction system where houses with a ground floor or two storeys one are usually

Traditional heavy frame house (Norsk Folkemuseum, Oslo). Photo: Eduard Correal Mòdol. INCAFUST.

erected. Rarely are there three storeys.

The heavy frame was the first wooden construction system using sawn elements of a rectangular section. Such was its importance that it was the predominant construction system in homes and civil buildings until 1830. Not surprisingly, the original medieval old towns that are still standing are full of this type of construction, easily identifiable by the wooden elements seen on the façade. In its purest conception, the saw is adapted to the sizes of the logs to optimise the material and as a result the beams and columns do not have standard sizes. So much so that in some variations of this system, large curved logs are even used so that they act both as a column and under-roof truss. The elements are joined together by fittings, some of them real works of craftsmanship. Normally, tools are never used and nails are very limited. Wooden pegs can be used to fix the pieces together and the frames are stiffened with backfill masonry. The dimensional limitations of the logs, the rigidity of the joints and the conception of the system itself mean that the typical maximum building height is three storeys, although it is not unusual to find five or six. This system was revived in the 20th century with the development of glued laminated timber. (Photos p. 8 and p. 9).

Heavy timber truss bridge (Lincoln, New Hampshire, USA). Photo: Eduard Correal Mòdol. INCAFUST.

Traditional Norwegian light frame house (Norsk Folkemuseum, Oslo). Photo: Eduard Correal Mòdol. INCAFUST.

From 1830 the heavy frame was gradually abandoned in favour of the light balloon frame, a system that was most popular in wooden houses until around 1930. This type of construction, common in North America, is characterised by its lightness, which is the opposite of stone houses or houses with a concrete structure and ceramic enclosures. Also using rectangular sawn timber, the main differences with the heavy frame are the use of much smaller standard-sized sections that are stabilised with sawn timber bars arranged diagonally at the corners joined with many screws, nails and tools instead of joints. The use of the material is therefore greatly optimised and there is no need to depend on any carpenters. As a result, with this system almost anyone could build their own house with their own hands inexpensively. Its main limitation is the building height, which is entirely dependant on the length of the studs. Although the panels are used as enclosures, they also provide rigidity to buildings. The highest typical house with a light frame is three storeys. (Photo bottom left).

Alongside the emergence of light frame buildings, timber frame structures emerged, combining rectangular sawn timber sheets and metal screws. This construction solution, which was competitive between 1830 and the 1940s, made it possible to go beyond basic timber construction by combining simple structural elements. In Catalonia, the former bleaching warehouse of the Cooperativa Obrera Mataronense by Gaudí (1883) and the headquarters of the Cartographic and Geological Institute of Catalonia in Barcelona (1929) are two excellent examples of this.

From 1930, the balloon frame quickly evolved into the platform frame due to obvious sectorisation issues in the event of fire. As it was vertically continuous between floors in the exterior façade walls, the fire could spread very easily through the insulation. The solution was to extend the floor structure over the entire floor up to the façade. This means that the studs no longer run the entire height of the house, but are limited to a length equal to the height of one floor. So, while in the balloon frame the floor structure is fixed to the frame, in the platform type it is supported. Another factor that plays in favour of the platform frame over the balloon frame is the more affordable cost of short studs compared to long ones. In retrospect, it may seem that this system eliminates the height limitations of the light balloon frame, however, the low load-bearing capacity of the small-section frames and the limited rigidity of the system mean buildings no taller than three storeys.

The tallest wooden buildings built or under construction are between eighteen and twenty-four storeys. The most ambitious current projects aspire to eighty.

The maximum expression of construction systems based on linear structural elements are the large structures made for building pavilions, large public buildings, bridges and above all large domes. Not surprisingly, wooden constructions hold the world record for a clear span between columns, reaching more than 100 metres. These milestones could not have been achieved until glulam reached a stage of development and performance comparable to that of today. In the 1940s, the new formaldehyde resorcinol glues, capable of withstanding more severe humidity and with a higher adhesion than traditional glues, made mass production of this material possible. In 1963, the first standard was published in America.

However, from the beginning of the 1990s, cross-laminated wood was developed. This material is manufactured by gluing an odd number of layers of solid wood sheets arranged crosswise. This results in panels with a high load-bearing capacity, where the unique characteristics of the wood is considerably less prominent. The intensive use of wood benefits acoustic insulation, improves thermal inertia compared to other systems, provides a great feeling of solidity and above all allows constructions to be built at height. We are currently in the midst of an undeclared competition to build the tallest building out of wood. It has gone from Waugh Thistleton's Timber

Modern detached house with light frame and OSB panels (Torrefarrera). Photo: Eduard Correal Mòdol. INCAFUST.

Complex column-free structure built with modern carpentry materials. Photo: Eduard Correal Mòdol. INCAFUST.

Tower in London with nine storeys in 2010, to the 85.4 metre Mjos Tower in Brumunddal (Norway) and to future projects that exceed 300 metres.

Until now, the typical structures regardless of the material are built with linear elements (beams and columns) and at most, as with the light frame, the partition panels give rigidity to the system. Conversely, pure CLT structures are erected using only panels and are based on the box concept. While an open box features many degrees of freedom, once it is closed, it becomes a highly rigid system. However, if the expected loads require reinforcing the structure, steel beams and columns can be used or even mixed structures can be designed. See photos.

02. Technological context of the evolution of timber constructions

Throughout history, the methods used for building with timber has significantly evolved. There are many reasons for these changes and many of them are seemingly unrelated to construction or to timber. The basis for all the developments that have taken place lies in the 'enclosure acts' that preceded the industrial revolution in the United Kingdom. The improvement in land productivity, the consequent expulsion of labour from the countryside and the lowering of wages due to the oversupply of this social class were the necessary breeding ground for the industrial revolution. In the second half of the nineteenth century, the creation of factories, the ability to obtain large quantities of resources, the reduction of distances thanks to motorised transport and the new specialised and chain-based forms of production based on Taylorism led to the standardisation of products. Artisanal and non mass-produced products lost much of their competitiveness.

> Building with timber today is fully planned, computerised and mechanised, and has surpassed conventional construction by evolving into modern manufacturing.

In this context, many new materials, machinery and products directly or indirectly related to wood emerged: screws and nails produced on an industrial scale, wood sawn in steam-powered sawmills (1830) and strong glues. Other products were also invented that were direct competitors such as Portland cement and rolled steel, and as a result construction with concrete and steel developed. Timber construction moved away from heavy frames and evolved towards light balloon frame and reinforced timber.

Single-family house in CLT (Lleida). Photo: Eduard Correal Mòdol. INCAFUST.

Building between CLT partitions. Ground floor plus five floors (Lleida). Photo: Eduard Correal Mòdol. INCAFUST.

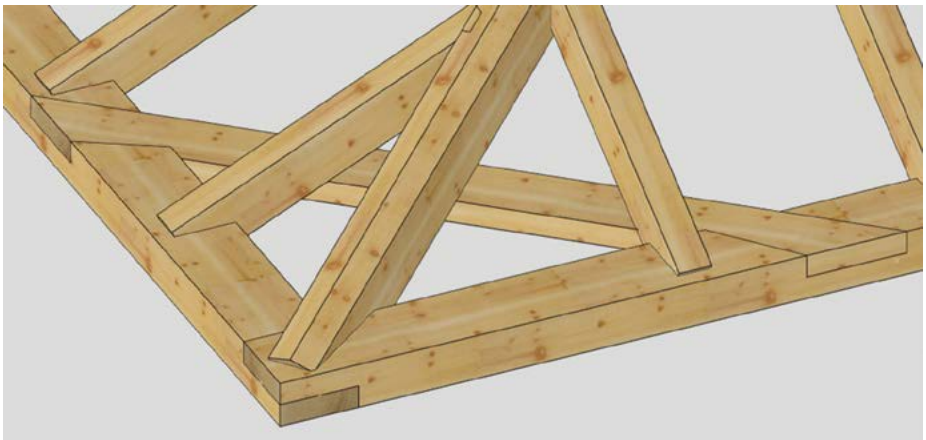
Wood craftsmen lost ground to standard-sized timber and joints made with nails, screws and tools. From this point on, there was relatively little further development with the adoption, years later, of light platform frames to improve fire safety and acoustic comfort for occupants. Also, short sawn timber was cheaper, easier to handle and transport than long sawn timber.

The future of construction involves renewable, sustainable, biodegradable, energy-efficient, insulating and breathable products. The future is wood.

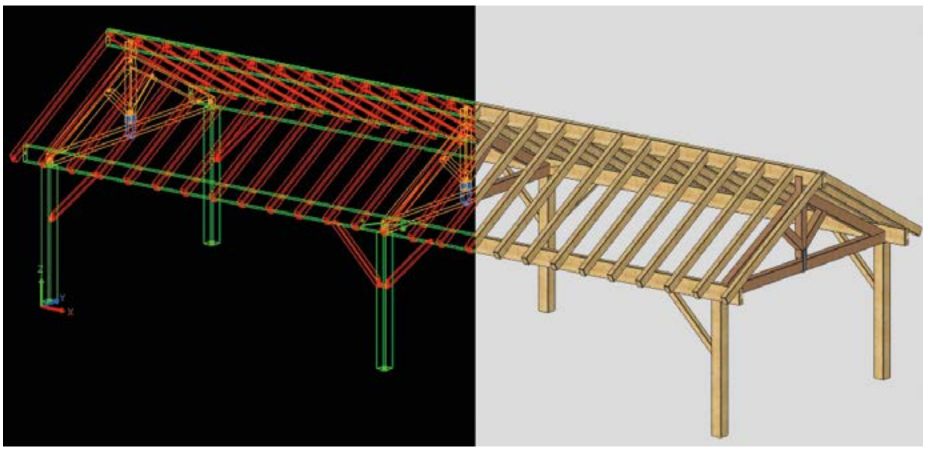
Generally speaking, the twentieth century was very good for concrete and steel construction, especially in the Mediterranean countries. In short, it can be concluded that, in countries where wood is a very abundant resource, such as the USA, the Nordic countries and Canada, these systems are economically efficient as long as energy remains cheap and the environmental costs generated at the end of their useful life are kept outside these countries. This is facilitated if, as happened in the 19th and 20th centuries, all new materials are considered as better per se. These new materials were designed and produced during a time of great technological evolution, when there was no ecological awareness and the economy was consumer driven and completely linear.

However, in terms of wood technology, the 20th century is a very important period where great advances were made in materials and tools. The development of polyvinyl acetate, melamine-formaldehyde, resorcinol-formaldehyde and polyurethane adhesives opened the door to the manufacture of particle board, medium density board, OSB, plywood, glued laminated timber, beyond that made with casein glue and cross-laminated timber, as well as many other mixed carpentry products. On the other hand, screws and tools also underwent a major evolution in the last century, a process that still continues to bring about new and improved structural solutions.

Another extremely important development, especially in the second part of the 20th century, was the development of computer systems and their application in CAD-CAM systems (Computer Aided Design and Computer Aided Manufacturing). The progressive increase in hardware computing power, the emergence of increasingly versatile and robust programming languages and cheaper equipment made it feasible to extend CAD software to a large number of users. On the other hand, advances that seem so obvious today, such as standardised communication protocols between equipment, telematic networks and the introduction of electronics in all types of industrial machinery, made CAM systems possible. The use of CAD design and CAM manufacturing in timber construction opened the door to manufacturing buildings in factories and achieving millimetre precision in building construction in the 1990s. The implementation of BIM (Building Informa-



Joint detail of a heavy frame structure. Currently they have not fallen into disuse thanks to CAD-CAM systems. Source: Salomé Temiño Villota



Structure designed and calculated with CAD ready to be sent to a CAM. Photo: Eduard Correal Mòdol. INCAFUST.

X-RAD system from Rothoblaas, an example of tools for highly complex structural joints for new generation construction solutions with CLT. Photo: Eduard Correal Mòdol. INCAFUST.

tion Modelling) systems in CAD-CAM constructions is much simpler than in conventional construction.

In any case, in Catalonia the exemplary building of the second half of the 20th century is a residential block of flats built with concrete, steel and ceramic materials. There are many reasons for this, but for this model to be competitive, a number of conditions must necessarily be met; a large pool of affordable labour, it must not be subject to strict occupational health and safety legislation, the large amount of waste generated at the end of the building's useful life must be carefully managed and cheap energy must be available to cool and heat homes and manufacture the necessary materials. This does not mean that such buildings cannot be built safely or designed to be efficient, but that meeting these new goals makes them less economically competitive than other alternative building systems. As a result, building methods that were once discarded have become very appealing.

03. Future trends

We are currently in the midst of rapid and profound change. In recent years, we have seen growing concern about the serious problems caused by the greenhouse effect combined with rising energy prices, due, in part, to the depletion of oil resources. In this sense, the Technical Building Code already incorporates limit values for energy demand, making building efficient homes mandatory. The transition from the linear consumer economy to the circular economy has already begun and any product, including buildings, that is not fully recoverable and re-introducable into the material cycle or that generates waste will not be acceptable. The rise in labour costs, the elimination of low-skilled jobs, the improvement of working conditions in terms of health and safety create serious problems in all labour-intensive sectors, including construction. In addition, the demand for healthy buildings that incorporate natural products and dispense with harmful products is becoming increasingly important. In any case, carpentry products are renewable, sustainable, biodegradable, low-energy intensive, naturally insulating and breathable, technological, resistant, optimised and efficient, and have a great future in construction. Because of all this, it is plausible to think that the various construction systems will hold a much more significant place in our homes than they have done until now.

To find out more

Structural Timber Association:
https://www.afe.cat/

Forest Bioengineering Solutions:
http://www.fbs.cat/

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http://www.incafust.cat/

Polytechnic University of Barcelona. Laboratory of Innovation and Technology in Architecture: https://lita.upc.edu/ca

Author

Eduard Correal Mòdol
Dr. Engineer.
Catalan Institute of Wood.
CTFC.
eduard.correal@incafust.cat

Jaume Avellaneda Diaz-Grande
Dr. Architect.
Laboratory of Innovation and Technology in Architecture.
LiTA. UPC.
jaume.avellaneda@upc.edu

ENERGY EFFICIENCY in timber construction

01. Introduction

Buildings account for 40% of total energy consumption and 36% of CO_2 emissions in the European Union (Annunziata, 2013). Therefore, with the aim of reducing energy demand, the European Directive 2010/31/EU on the energy performance of buildings was introduced in 2010. According to this directive, all new buildings must be *nearly zero energy* buildings ("nZEB") from 31 December 2020 (two years earlier in the case of public buildings). The directive was amended in some aspects in 2013 and 2018 (directive in force: 2018/844/EU). Different countries are currently incorporating the corresponding energy assessment definitions, indicators and methods into their national building codes. In Spain, the Basic Document is being prepared for the update of the Basic Document DB-HE, for the update of the Technical Building Code (CTE).

On the other hand, buildings consume between 20% and 50% of natural resources, depending on the environment where they are located (Ramírez, 2010). Responsible resource management is another aspect on the European agenda as demonstrated by the social challenge included in the Horizon 2020 research and innovation programme on climate change, environment, resource efficiency and raw materials. Furthermore, one of the sustainable development goals adopted by the UN is the responsible production and consumption of resources. In order to achieve the aforementioned goals, the ecological footprint of materials need to be taken into account and aim to reduce the environmental impact of the materials used during the construction of a building.

Wood can respond to the dual challenge of achieving high energy efficiency and sustainable use of natural resources.

In this context of high energy and environmental requirements, the use of wood and its by-products could be key. The use of certified wood guarantees responsible and sustainable management of forest resources. This makes wood a renewable resource, as demonstrated by the growth in forest cover in Europe since 1990 (Kauppi, 2018).

02. Thermal behaviour of wood and its by-products

Wood has a low thermal conductivity compared to other materials used in construction and a very high specific heat, from 1600 to 2900kg°C, which means that, with the same supply of heat, it heats up less than other materials.

02.01. Thermal insulation

Among other considerations, the current DB-HE of the CTE establishes the minimum requirements for the thermal transmittance of buildings. These requirements vary according to the different climate zones defined in the document. In order to determine the thermal transmittance of a given building, the thermal conductivity of the materials it is made of is needed. For the same material thickness, the lower the thermal conductivity, the higher the thermal resistance and the lower the energy losses.

The thermal conductivity of wood depends on the type of wood and its densi-

Type of Wood		ρ (kg/m3)	λ (W/m·K)
Hardwood	Very heavy	ρ >870	0.29
	Heavy	750< ρ ≤870	0.23
	Medium weight	565< ρ ≤750	0.18
	Light	435< ρ ≤565	0.15
	Very light	200< ρ ≤435	0.13
Softwood	Very heavy	ρ >610	0.23
	Heavy	520< ρ ≤610	0.18
	Medium weight	435< ρ ≤520	0.15
	Light	ρ ≤435	0.13

Table 1. *Thermal conductivity values (λ) for two types of wood, depending on their density (ρ). Source: prepared by the authors from the data of constructive elements of the CTE.*

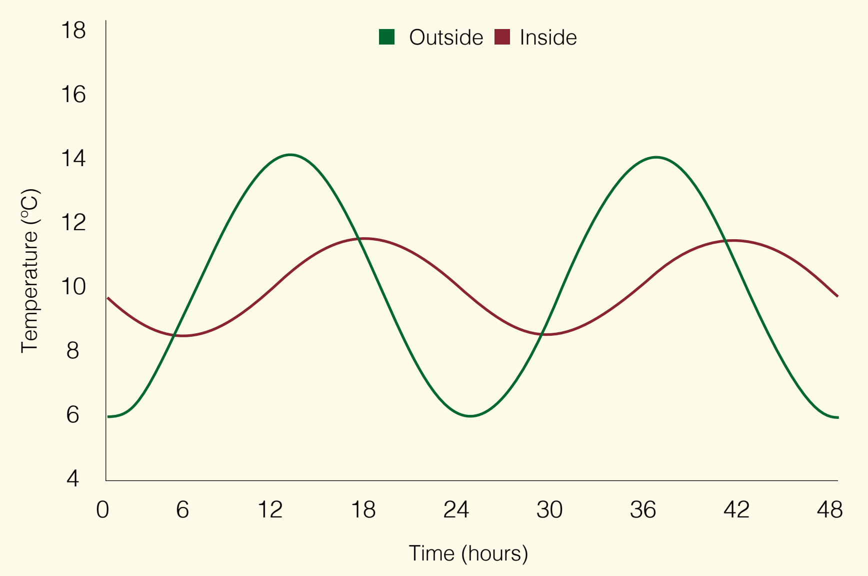

Figure 1. *Diagram showing the variations in outside and inside temperature over the course of two days, as well as the delay expressed in hours. Source: Prepared by the authors.*

	conductivity λ (W/mK)	Diffusivity α (m2/h)	Delay ϕ (hours)
Aluminium	230	0.3485	0.2
Air	0.026	0.0755	0.5
EPS insulation	0.035	0.0076	1.6
Wood fibre insulation	0.04	0.0025	2.8
Concrete	1.35	0.0024	2.8
Glass	1	0.0019	3.2
Perforated brick	0.49	0.0018	3.3
Cork	0.049	0.0009	4.5
Wood	0.13	0.0004	7.3

Table 2. *Values of the thermal conductivity and diffusivity of different materials and the delay corresponding to 10 cm thickness. Source: Prepared by the authors.*

Assembly of the structure with light wooden frame and of the thermal insulation of the façade, respectively. Photos: House Habitat

ty, but in all cases it has low values. Table 1 shows the corresponding values for softwood and hardwood. The thermal conductivity of wood is typically 4 times lower than that of brick, 10 times lower than that of concrete and 2,000 times lower than that of aluminium (Table 2).

Wood by-products also have low conductivities, such as plywood boards, or particle boards and fibreboards with conductivities that vary between 0.24 and 0.07 W/mK depending on the density of the board. Oriented strand board (OSB), widely used in light frame timber construction, has a conductivity of 0.13 W/mK. Whereas cork and wood fibre panels have thermal conductivities similar to those of other thermal insulators such as mineral wool and polystyrene foams.

02.02. Thermal inertia

The U-value transmittance is the most commonly used parameter to assess the thermal performance of a building and to comply with regulatory requirements. However, in order to design energy efficient buildings it is necessary to also take into account their dynamic behaviour (thermal inertia). Numerous studies show that the use of walls with high thermal inertia in buildings, in addition to improving indoor comfort, can lead to a highly significant reduction in energy needs, both for heating and cooling. In fact, the best energy efficiency is given by a combination of the two factors (transmittance and inertia), suited to the situation and type of use of the building.

The temperature of the outdoor environment in a building varies with time, throughout the daily cycle. If the temperature variation in the indoor environment has a large delay and a small magnitude compared to the outdoor variations, the building is said to have

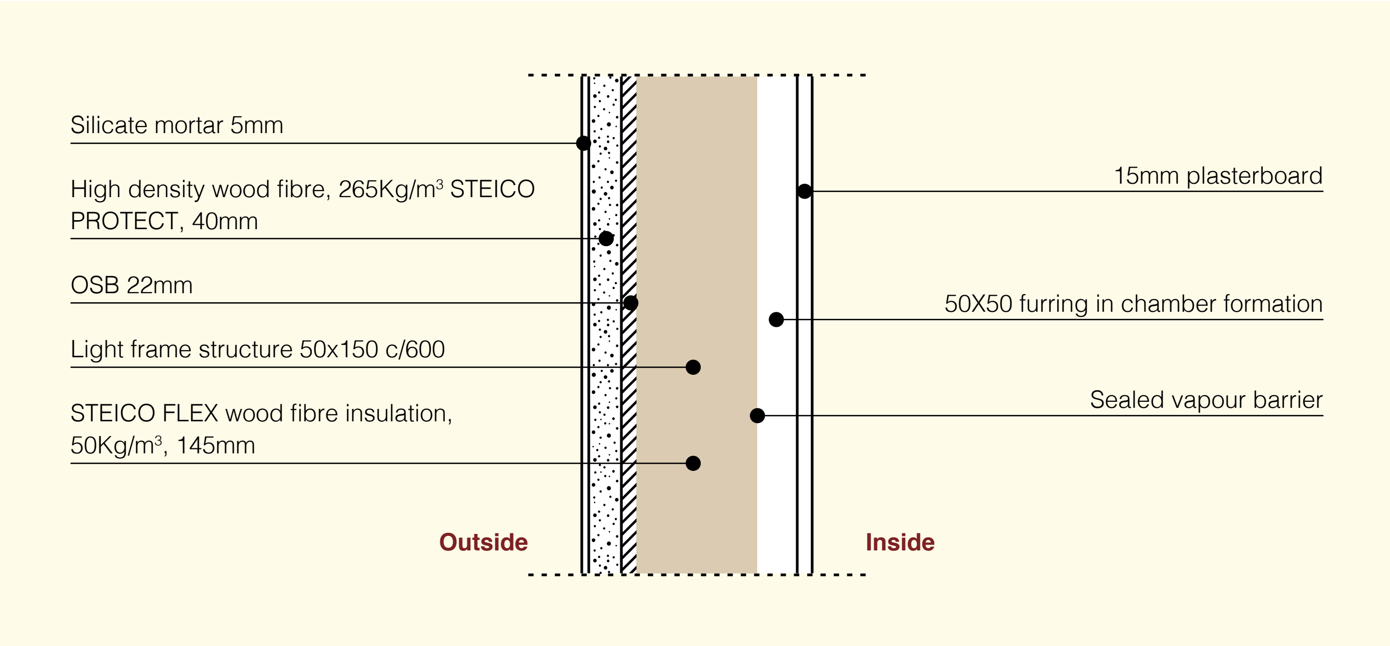

Figure 2*. Elevation section of the façade of the house. Source: House Habitat.*

a high thermal inertia. Figure 1 shows schematically the time delay (φ), measured as the difference, in hours, between the time when the maximum temperature occurs outdoors and the time when it occurs indoors.

For a wall of a certain material, the delay and damping are more significant the thicker the wall and the lower diffusivity of the material. On the other hand, the diffusivity of a material (α) depends on the thermal conductivity (λ), the density (ρ) and the specific heat (c): $\alpha=\lambda/\rho c$.

The combination of the three properties gives wood a very low value compared to materials such as concrete and glass.

Table 2 shows a comparison of the thermal conductivity and thermal diffusivity value of different materials, as well as the time delay for the same material thickness of 10cm. The performance of wood is particularly noteworthy, for which there is typically a delay of 7 hours for a thickness of 10cm. It is also very interesting to note that wood fibre thermal insulators show a thermal conductivity similar to other insulators such as EPS, but a much lower diffusivity and therefore give a longer delay. This is even more so in the case of cork insulators, which has a delay almost 3 times longer than EPS.

03. Timber construction systems

There are different types of timber construction systems. In simple terms, we can classify them as massive systems and framing systems. Massive systems include log houses and constructions with cross-laminated timber panels (CLT). Whereas, frame systems can be classified as heavy and light (Guide to Building with Wood).

In our environment there is a growing interest in constructing new buildings with wood and the most commonly used construction systems are light frame and CLT panels.

Light frames is a system that emerged in the United States at a time when flexibility in design and the ability to build with no special tools were highly desirable advantages. Unlike the heavy frame system, small pieces of wood are used. The closures can be made in different ways, such as with plywood boards or OSB boards. It is a system that can be built on site, but also supports a high degree of prefabrication.

Wood has relatively low values of thermal conductivity and very low thermal diffusivity. This means that wood, compared to other construction materials, has good thermal insulation and a high thermal inertia.

Cross-laminated timber panels consist of an odd number of planks, usually 3, 5 or 7, of sawn timber glued together perpendicularly. Formaldehyde-free glues based on polyurethane resins are the most commonly used glues in CLT production. The arrangement of the planks means CLT can be used in both vertical and horizontal elements, giving the panel high dimensional stability.

Timber construction combined with other measures specific to a passive house makes high energy efficiency possible.

Although wood is relatively insulating compared to, for example, concrete and bricks, it is not enough to meet today's energy saving standards and requires, as with other conventional building systems, the incorporation of thermal insulation panels. In prefabricated timber construction systems, these insulators can be incorporated directly in the factory, which facilitates assembly and reduces build times. On the other hand, in order to enjoy the environmental advantages of wood and other lignocellulosic materials, there are wood fibre and cellulose insulation materials available.

Figure 3. *Label with the energy rating of the home. Source: House Habitat*

Wooden homes incorporating a suitable level of thermal insulation and other energy efficiency measures can achieve energy classifications as stringent as passivhaus certification.

An example of this is a project by the company House Habitat located in the municipality of Castelldefels (Barcelona) and certified as a passive house. It is a house with a light frame structure of Nordic pine from sustainably managed forests. The façade cladding consists of low-density wood fibre thermal insulation, sandwiched between the light timber frame (see photos p. 16), 22mm OSB 4 panels, and with a composite finish of a SATE system, using high density wood fibre panels and coated with silicate mortar, as illustrated in figure 2.

Among other things, the house includes forced ventilation systems and energy generation from renewable sources. These factors combined results in an annual energy consumption of 22kWh/m^2 and low CO_2 emissions of 3kgCO_2/m^2. These low values mean that it has an energy rating of A (fig.3)

To find out more

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Author

Alina Avellaneda
Associate Professor.
Department of Architectural Technology. UPC.
alina.avellaneda@upc.edu

Laia Haurie
Assistant Professor.
Department of Architectural Technology. UPC.
laia.haurie@upc.edu

Ana Maria Lacasta
Professor.
Department of Architectural Technology. UPC.
ana.maria.lacasta@upc.edu

MYTHS AND REALITIES about timber construction and its fire performance

In recent years, timber has become popular again in the construction industry. The development of new timber/wood products with excellent performance and the growing awareness of their environmental impact have contributed to gradually being used in all types of buildings. However, some reluctance persists, such as the negative perception of its fire performance as a combustible material. Many users and professionals ask the INCAFUST technical office about this very issue.

Saldos Arias building fire (Madrid – 1987). Part of the old wooden structure of the building had been replaced by steel profiles in previous renovations. The part that maintained the wooden structure will remain standing. Victims: 10 firefighters. Source: Madera y fuego. Cátedra Madera. University of Navarre.

The fire reaction classification limits the use of wood and its by-products in certain applications defined in the DB-SI of the CTE.

While it is true that wood and its by-products are combustible materials due to their anatomy and chemical composition, it is also true that in a fire wooden structures can achieve fire resistance times equivalent to or even longer than concrete or steel structures (fig.1). In fact, since the Technical Building Code (CTE) came into force, buildings with wooden structures must comply with current rules and regulations on fire safety, just like other building materials. From this perspective, they should not pose a greater risk to people in the event of a fire.

The fire performance of building materials, products and elements is understood based on the two fundamental concepts that define it: the reaction of materials and products to fire, and the fire resistance of building elements. Reaction to fire refers to the ability of a material to contribute to the de-

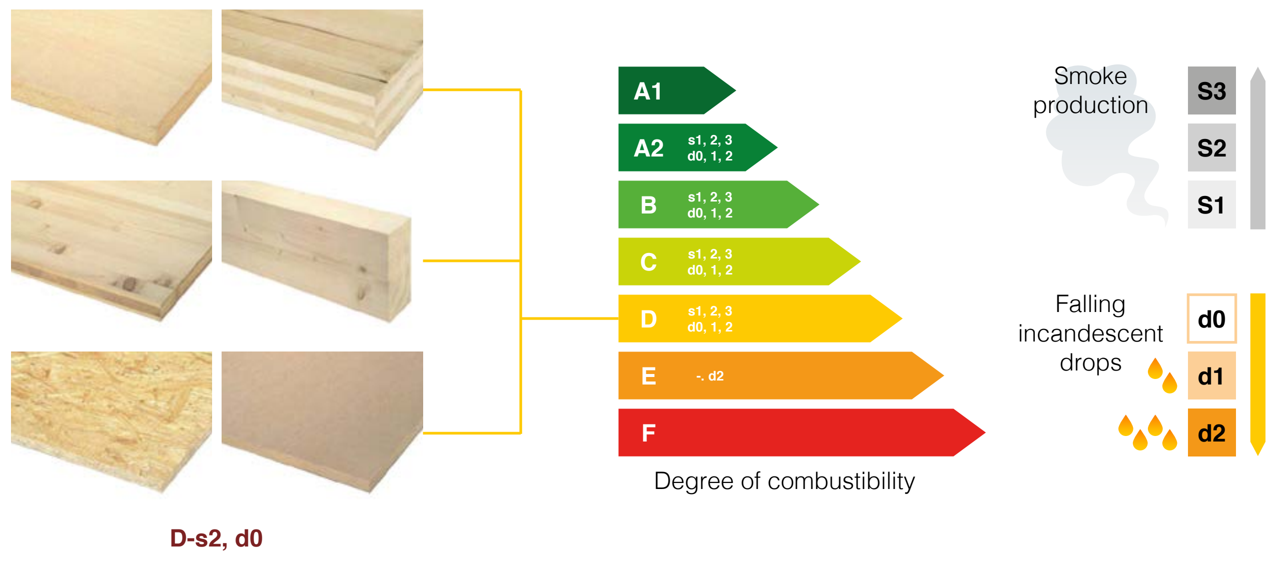


***Figure 1**. Fire reaction classification of wood and its by-products. Source: Prepared by the authors.*

velopment of fire. While fire resistance defines the ability of a building element (column, beam, wall, etc.) to maintain its required load-bearing function (R), integrity (E) and/or thermal insulation (I) for a certain period of time, in a time scale ranging from 15 to 240 minutes. According to the common framework established by the European Commission (Euroclasses), the fire class for wood and all its by-products is D-s2,d0 (fig.1), which indicates that it is a combustible material with an medium-size contribution to fire, producing a moderate amount of smoke and no incandescent droplets or particles. This classification penalises using wood and its by-products in certain applications as set out in the basic fire safety document (DB-SI) of the CTE.

Wood is mainly made up of cellulose, hemicellulose and lignin. As these are composed of hydrogen, oxygen and near 50% carbon, they are combustible and flammable (flame-producing).

Mass is a key factor in defining the fire resistance of a timber structural element.

Wood burns, but not in the same way in all instances. It burns relatively easily on the surface. However, when the mass of the material increases to form an element with sufficient cross-section, it is harder to initiate the ignition process. A temperature of around 270-300ºC is required for a certain period of time before the material starts to give off vapours due to moisture loss and subsequently starts to burn (fig. 2).

The combustion process of a massive piece of wood also occurs significantly slower. This phenomenon is technically known as smouldering. During combustion, which is simply the degradation of wood by the action of fire, a chemical process called pyrolysis takes place. The pyrolysis front slowly progresses through the mass of the element and results in a surface carbon layer that protects it from heat and flames, preventing outgassing and oxygen from entering the interior.This is the charing rate. The char of the surface is a kind of natural "intumescence" with considerable insulating capacity, as charcoal is up to six times more insulating than wood. The internal part of the constructive element remains practically intact, with its physical and mechanical properties unchanged (fig.3). Therefore, the loss of load-bearing capacity that occurs in a structural piece of wood under these conditions is due to a reduction in the cross-section, but not to a reduction in the strength of the material. Solid wood therefore burns gradually and predictably. The charring rate is estimated to be around 0.7-0.55 millimetres per minute depending on the density and hardness of the species, which is fundamental in calculating the size of structures.

Solid wood elements demonstrate good fire performance primarily due to the thermal properties of the material, especially the low thermal emissivity and conductivity. On the other hand, wooden structures have a very low thermal expansion, so they do not cause stress between elements or thrusts in the walls. This is very important in a fire because it minimises the chances of the structure collapsing.

***Figure 2**. Wood burns more or less easily depending on the mass of the element. Photos: Timber fire behaviour. Roberto Tomasi. Lund University.*

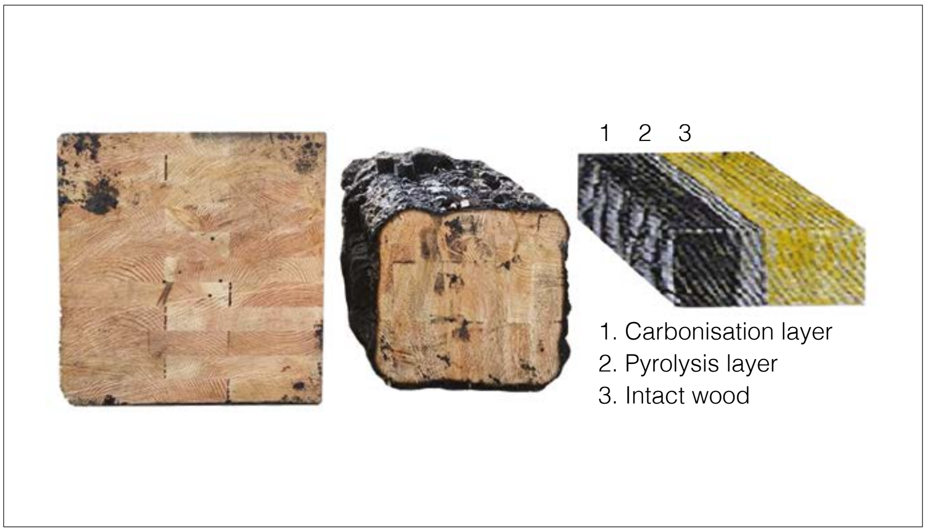


***Figure 3**. Comparison of section reduction of a glulam weight in fire. Stratification of wood in fire. Source: Thinkwood. Tests carried out by Arup fire. Peraza, 2001.*

Fire station 76. Oregon, USA. Hennebery Eddy Architects. Fire station built entirely out of wood. Photo: Archdaily.

All this means that wooden estructural elements are an excellent option for building fire-resistant structures (see photo at the bottom of the page).

Fire protection and regulations

Fire safety regulatory framework consists of a set of general regulations and local regulations applicable to building and testing standards for products and systems, some of which are harmonised in Europe. The DB-SI of the CTE is a document that includes the general fire safety regulations for buildings, and the RSCIEI (Fire Safety Regulations in Industrial Establishments) for industrial premises. The regulations establish the limit values and minimum requirements that buildings must meet in order to achieve the permissible safety levels depending on the evacuation height and occupancy.

The protective measures may be implemented differently according to the characteristics of the project. They can aim to strictly comply with the requirements of prescriptive regulations or apply performance-based fire protection engineering strategies combining passive and active protection measures. Some experts point out that the latter are more appropriate to address fire safety in timber-framed buildings due to their unique fire performance. The performance-based fire safety codes and methods are based on the PBD (Performance Based Design) concept that has been widely used for years in northern European countries, New Zealand, the USA, Canada and other countries. All of them are distinguished by an important presence of wood in the construction industry.

Whatever the safety strategy used, prevention and control measures are based on the aspects listed in table 1.

It is currently possible to build all types of timber-framed buildings capable of meeting the fire safety requirements of any regulatory framework. Numerous examples of national and international buildings confirm this.

The fire resistance of structures and partitioning elements (for separating fire sectors) can be determined using the calculation basis contained in Annex SI E of the CTE and Eurocode 5. The load-bearing elements are designed and sized according to the strength required in each case. Partitioning elements may consist of several layers of boards that form a system. The number of layers depends on the required resistance value. In some cases, boards of non-combustible materials are used which, in addition to the protection they provide to the system as a whole, allow the surfaces to meet fire reaction requirements on the wall surfaces. These boards are usually made of plasterboard, fibre-silicate or wood cement with a fire classification of A1 or A2. These types of protective boards are called Class K boards, and the complete system they protect is called encapsulation. The effectiveness of the construction solutions proposed in each case is usually validated by large-scale laboratory tests.

Technical wood products such as Glulam structural elements and Cross Laminated Timber (CLT) panels have a performance equivalent to that of solid wood in a fire. So, they can reach high fire resistance times. In Canada, as part of a technological transformation project, CLT structural panels (under load) were submitted to fire resistance tests reaching maximum resistance values of 113 minutes for wall panels (5 layers) with no protection boards and 178 minutes for flooring (7 layers) with no protection boards. Data such as these reflect the structural reliability of solid wood in a fire (fig. 4).

Flame retardants

Current regulations limit the use of timber cladding in certain applications (walls, ceilings and floors in habitable spaces, evacuation routes, façades, etc.) due to how they react to fire. The carbonisation effect, which decisively favours timber structures, is not significant in thin elements such as cladding panels, slats, panels, etc.

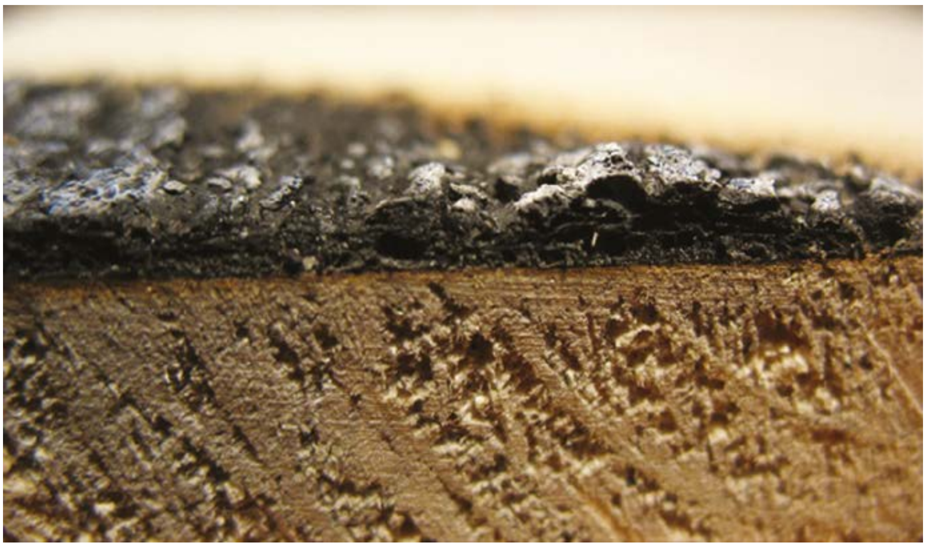
Flame retardant treatments are a good option to obtain a better fire reaction classification for wood elements and products. Wood treated with fire retardants can achieve C or B classifications and S2 and S1 smoke production rates. However, it should not be forgotten that wood is a combustible material, so the use of fire retardants can improve its fire reaction characteristics, but does not change the nature of the material. In this sense, fire-retardant wood may be a misnomer.

<table>
<tr><th colspan="2">Measure</th><th>Requirement</th><th>Type of Protection</th></tr>
<tr><td colspan="2">Design and sizing of structural elements.</td><td>(R)</td><td>Passive</td></tr>
<tr><td colspan="2">Design of partition elements</td><td rowspan="2">(EI) (REI)</td><td rowspan="2">Passive</td></tr>
<tr><td>Horizontals: floors and ceilings.
Verticals: walls and façades.</td><td>Framing systems.
Solid wood panel systems (CLT).</td></tr>
<tr><td colspan="2">Automatic sprinklers</td><td>Justification of alternative protection strategies to the regulations.</td><td>Active</td></tr>
<tr><td colspan="2">Evacuation routes and detection, alarm and extinguishing elements.</td><td>Evacuation, control of internal fire spread/justification of alternative protection strategies to the regulations.</td><td>Passive/Active</td></tr>
<tr><td colspan="2">Construction details, seals and fire barriers.</td><td>Control of the internal and external spread of fire.</td><td>Passive</td></tr>
</table>

Table 1. *Aspects to consider in fire prevention and control measures; requirements and type of protection. Source: Prepared by the authors.*

Brock Commons Tallwood House. UBC, Vancouver campus. Acton Ostry Architects Inc. Currently, the tallest building in the world with a wooden structure (18 floors). Photos: maisons-bois.com.

***Figure 4**. Tests of CLT cross-laminated timber panels. Photos: FP Innovations Canada.*



Effect of an intumescent paint in contact with fire. Photo: Teknos

There are various retardant products on the market that act on the surface in different ways in order to delay the ignition and combustion processes. Some retardants work by encouraging carbonisation (catalytic effect), others by forming a film that prevents surface contact with oxygen, others by releasing non-flammable gases (water vapour, ammonia and CO_2) that dilute the combustible gases. There are also those that form a layer that swells and isolates the surface by excluding oxygen and preventing the escape of combustible gases, as in the case of intumescent paints and varnishes (bottom photo).

According to their composition, they can be divided into inorganic, halogenated, organophosphorous and nitrogen-based.

Inorganic products are the most commonly used in lignocellulosic materials such as wood, especially phosphorus-based compounds such as phosphoric acid, melamine phosphates, ammonium phosphate (often used in intumescent products and paints) and potassium phosphate. Some of these compounds could, eventually, reduce the mechanical resistance of the wood when the elements are permanently subjected to high temperatures, for example, in roof structures with high solar incidence.

Boron-based water-soluble salts are also widely used, such as boric acid and sodium tetraborate, commonly known as Borax. These products, although very effective, are only suitable for indoor use as they can easily be washed away in the rain. Currently, there are products available based on non-water soluble borates such as zinc borate. However, the best option for outdoor use (façades, slats, pergolas, etc.) are paints. These products are

Paints for façades with flame retardants. Photo: Teknos

highly durable in adverse weather conditions, and are often used to prevent fungal growth. The main drawback is that it is an opaque finish that covers the wood with a uniform colour, hiding the grain of the wood. This type of different coloured paint is widely used in northern Europe.

Nitrogen-based compounds have become popular thanks to their environmental properties. Their level of toxicity and smoke emission is low compared to other retardant substances. One of the downsides is that large concentrations of the product are required for it to be effective. This aspect could influence the mechanical behaviour of the treated material.

Another important aspect of retardant products is the type of application. The degree of effectiveness and durability of the treatment largely depends on this. Application processes can be surface or deep. Surface processes include:
-Brushing: it is applied to the surface of the wood. Varnishes or paints are usually used.
-Spraying: it is a slightly more controlled treatment compared to brushing. A sprayer is used to give a more uniform application. As with brushing, the products applied are varnishes and paints.
-Immersion: involves immersing the element to be treated in a water-soluble solution. The product penetrates the material by absorbing the water and fills any voids as the water evaporates. In some cases, the solution is heated to improve absorption.

Deep or impregnation treatments are specialised processes using vacuum and pressure or double vacuum techniques with autoclaves. They consist of placing the product inside the porous structure of the material to achieve adequate product penetration and retention. This treatment allows other surface finishes to be subsequently applied.

To find out more

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Author

María Pilar Giraldo Forero
Dr. Architect.
Catalan Institute of Wood.
CTFC
pilar.giraldo@incafust.cat

Let's talk with JOHN SEBASTIA

Manager of Fustes Sebastia SL. Rialp (Pallars Sobirà). President of the Structural Timber Association of Catalonia (AFE).

Structural Timber Association
https://www.afe.cat/

Fustes Sebastià
http://www.sebastia.eu/

"In a few years, timber construction has gone from being a rarity to a real alternative to conventional technology and materials"

Joan Sebastia Colomé created the company Fustes Sebastia, SL with his brother and father in 1990. He has completed specific courses in the timber industry and, since 2017, he has chaired the Structural Timber Association of Catalonia, an organisation that brings together companies and professionals involved in the industrial mechanization and the assembly of timber structures, as well as complementary activities, such as the marketing of products and engineering services, among others.

Timber has carved a niche for itself in the world of construction and in recent years has become a fast, clean and sustainable alternative to conventional materials. Despite market reluctance, a change in the energy and environmental paradigm, a reduced workforce, improved working conditions and greater control on the construction site means that wood is rapidly gaining ground. We discuss the present and the future of this material in the construction industry with Joan Sebastia, who for more than 30 years has been at the head of Fustes Sebastia, SL, a company specialising in structural timber solutions and pre-fabricated low-energy buildings. He is the president of the Structural Timber Association of Catalonia (AFE), an organisation that works to promote timber in construction and to improve the qualification and competitiveness of companies in the industry.

The AFE is an organisation that brings together companies and professionals involved in the industrial mechanisation and assembly of timber structures, as well as complementary activities, such as the marketing of products and engineering services, among others. What are its goals? How many members does it currently have?

The AFE (www.afe.cat) was set up in 2005 to bring together industrial companies in the timber construction industry and we now have around thirty members. When it was founded, building with timber in Catalonia was a testament to the entire construction industry and hardly any houses were built entirely with timber, with major problems especially in terms of insurance. At that time it was necessary to lay the groundwork for the building revolution that is taking place.

The association brings together companies involved in the industrial mechanisation of timber structures and the manufacture of elements and components of timber construction systems; the assembly of timber structures and the installation of prefabricated timber elements for construction, as well as those with complementary or related activities to timber construction.

"In the future, we hope to further help promote timber in construction, improve the qualification and competitiveness of companies and work to defend members' interests in general"

The goals of the association are to defend its interests helping to increase the prestige and collaboration of its members and, in general, those of a commercial, economic and technical nature.

Could you give some examples of the activities you have completed or projects for the future?

Among other activities, the organisation defends, represents and promotes the commercial, economic, social and technical interests of its members; participates in national and international fairs, congresses and forums; organises and promotes seminars, technical conferences, congresses and other similar events that help the dissemination and technological discussion of the structural use of timber.

So, for example, various group participations have been organised for members in sectoral fairs such as Construmat, business trips to learn about other industry environments, courses and activities, publication of informative materials, etc.

In the future, we hope to further help promote timber in construction, improve the qualification and competitiveness of companies and work to defend members' interests in general.

How important is timber in the Catalan and national construction market?

It is hard to say what is the proportion of buildings made of timber compared to the total, but what is clear is that in a few years timber construction has gone from being a rarity to a real alternative to conventional technology and materials. As an example, there are currently public developers where around 50% of the public tenders awarded have been won by timber constructions. On the other hand, the market for single-family and multi-family houses is off to a strong start. Other examples are in Barcelona, where there is an eight-storey building, and in Cornellà de Llobregat, where an 85-storey building for social rent is currently being built.

What are the most commercially viable applications?

There are two main construction types that are appealing for their performance and versatility: the light frame and cross-laminated timber (CLT) buildings. Half-timbered houses are very efficient in their use of material, but their technology limits their height. This is an ideal building technique for single-family houses or up to two storeys. In contrast, CLT buildings are much more material-intensive in exchange for much greater structural possibilities. Buildings of more than thirty storeys are already a reality and there are proposals for up to eighty.

Which species/varieties of wood are most produced in Catalonia and which are most suitable for structural construction?

Catalonia is a forest country where conifers are predominant from an industrial point of view. Quantitatively, the most important are Scots pine (*Pinus sylvestris*) and black pine (*Pinus nigra*), but there is also mountain pine (Pinus uncinata), fir (*Abies alba*), Douglas fir (*Pseudotsuga menziesii*) and plane trees such as chestnut (*Castanea sativa*). However, many species have been traditionally used and beams of a wide variety of species can be seen in old buildings.

Do you think that timber gets sufficient recognition as a building material, both inside and outside the industry?

Large economic industries are, by definition, resistant to change and construction is no exception. The building tradition in our country has been based on stone materials and metals in recent decades. Changing this trend is a slow process, since there is great inertia and even resistance. However, the change in the energy and environmental paradigm, the reduction in the amount of labour, the necessary improvement in working conditions and in-

"There are two main construction types that are appealing for their performance and versatility: the light frame and the cross-laminated timber (CLT)" creasingly strict requirements for the control of materials and work processes mean that timber is gaining ground.

Wood is a rapidly growing material; What are its main advantages as a building material?

Wood is a very strong yet light, heat-insulating, sustainable and reusable material. If we combine these properties with industrial manufacturing technology, structures and buildings are produced with millimetric precision, the quality of execution is exceptional and energy-efficient solutions are easily achieved. Also, as wood is a natural material that regenerates in forests, unlike stone and metal materials, its environmental impact is much lower.

"Catalonia is a forest country where conifers are predominant from an industrial point of view"

Wood by-products allow for technologically advanced solutions. What are the main ones?

From an architectural standpoint, wood is an extraordinarily plastic material with infinite design possibilities. World records for the distance between columns have been achieved by using wooden domes and height is no longer an obstacle for building skyscrapers. The work is done extraordinarily fast. As it is a dry build, there is no need to wait for the mortar to dry and multi-storey timber structures can be erected in days. Building with wood is fast, clean and does not generate waste on site.

"Wood is a very strong yet light, heat-insulating, sustainable and reusable material"

"Building with wood is fast, clean and does not generate waste on site"

Wood is also a renewable and environmentally friendly raw material. What are the main environmental benefits from its use?

Wood is a renewable and reusable forest material that removes CO_2 from the atmosphere while in use, helping to fight climate change. Less energy needs to be used during its transformation than conventional materials. Because it is light, it is cheaper to transport in terms of energy used. Its insulating capacity optimises the use of insulation and minimises thermal bridges, therefore, cooling and heating costs during the life of the building are minimised. Manufacturing the various building elements in a workshop optimises the use of the material almost eliminating waste; therefore, no raw materials are wasted.

What do you think are the main future challenges for the industry?

Considering that technologically advanced carpentry materials are increasingly more available and that there are very professional companies such as those associated with the AFE that are capable of providing first-class solutions, the main challenge is to make the wider public aware of the possibilities of the material.

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