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THE USE OF STRUCTURAL TIMBER IN EUROPE: AN OVERVIEW ON RECENT DEVELOPMENTS

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Abstract

The prerogatives of sustainability, excellent strength-to-weight ratio and high prefabrication level, make the structural timber as a highly performant construction material widely used in Europe for new constructions or for retrofitting the existing ones. The recent development of structural timber was due to the introduction of engineered wood products that gave the possibility to realize buildings for residential and commercial destinations, also in seismic- prone areas. Moreover, in the light of the Next Generation EU Plan - released be the European Parliament as aid to the economy recovery following the covid-19 pandemic - which introduced the concept of green transition to reduce emissions of carbon dioxide into the atmosphere, timber surely occupies a prominent place among the building materials.

This paper deals with an insight on the use of timber in Europe as sustainable, green, and highly seismic and energetic performant construction material. The aim is that of providing a comprehensive overview on the state-of-art and highlighting recent advancements and future trends both in research field and engineering practice in Europe. Particular emphasis is paid to (i) new timber-based products and/or subassemblies used for low, medium and high-rise seismic-resistant constructions; (ii) timber-based solution for combined seismic and energetic retrofit of existing masonry and reinforced concrete buildings; (iii) new prospective of short chains to improve life cycle of material and its impact on environment, (iv) codes and guidelines. The peculiarities of each topic treated are discussed in detail.

Keywords: Structural Timber, Timber Products, Timber Buildings, Retrofit, Codes.

1 INTRODUCTION

Timber based constructions are spreading in Europe in the last two decades in order to pursue the growing need to have high-performance buildings, both from structural and energetic points of view [1,2]. In this context, the (relative) recent introduction of engineered timber products - such as Glue-Lam, Cross-Laminated Timber, Laminated Veneer Lumber, OSB, etc., realized with automated-control industrial processes - offered new possibilities in realizing timber-based structures with respect to traditional solid wood elements [3,4]. In addition to classic timber roofs, single or multiple span bridges, engineered products have led to the possibility of realizing new structural solutions for timber buildings in seismic-prone area, concerning fully timber low- or mid-rise constructions and hybrid structural solutions (i.e., that couples timber elements with concrete or steel) [5, 6, 7]. The growing interest towards the use of timber elements and the introduction of engineered timber buildings (both for residential and industrial sector) has motivated the scientific community to update the existing timber codes; the aim is that of align and transfer the scientific background concerning the seismic design rules developed for other construction type (i.e., reinforced concrete or steel) to timber structures [8, 9].

Due to the potentials offered by raw material - related to structural and environmental aspects - timber constructions strongly attracted the attention of the researchers in the last years, especially in Europe. Moreover, the Next Generation EU plan, released by the European Parliament following the Covid-19 pandemic, accentuated the use of timber products because particularly suitable in the framework of integrating structural performances and energetic aspects both for new buildings and for retrofitting the existing ones [10,11].

Looking at existing buildings, studies on the use of timber elements for retrofitting existing masonry and reinforced concrete buildings occupy a prominent position in the last two/three years in Europe [12]. Several solutions, mostly oriented to integrate seismic and energetic aspects, have been recently introduced in the scientific literature and other are under development.

The aim of the paper is to provide an overview on recent developments and trends concerning the use of structural timber in Europe, with particular emphasis on structural, energetic and short chain/life cycle aspects. The work is subdivided in three main Sections, organized as follows: Section 2 focuses on timber-based products available in Europe and the structural solutions mainly used for low-, mid- and high-rise timber buildings; Section 3 focuses on the potentialities offered by timber-based solutions for seismic and energetic retrofit of existing buildings and reports a state of the art on scientific studies conducted on this topic; Section 4 discusses about the new prospective of short chains to improve life cycle; Section 5 reports a brief recognition on codes and guidelines devoted to structural design of timber elements, subassemblies and buildings.

2 TIMBER-BASED PRODUCTS FOR LOW, MEDIUM AND HIGH-RISE BUILDINGS IN SEISMIC-PRONE AREA

2.1 Products

Thanks to technological innovations and research advancements, the performance of timber-based products become more and more excellent over the years. Basically, timber products were made by solid hard- or soft-wood elements in the past, whose dimensions were regulated by natural limits of base material. All the products illustrated in this section are summarized in the Tables 1, 2 and 3. Thereafter, the introduction of industrial production gave the opportunity to introduce on the market the so-called *engineered timber products*, where Glue-Laminated Timber (GLT) surely represents the emblematic example [13]. On the other hand, also glued solid wood elements are performant products, such as the KVH whose main advantage is that of using solid wood element joined with finger joints along its longitudinal axis; thus, they represent a right compromise between solid and GLT to realize one-dimensional timber elements used for beams and columns (https://lnx.dartalegno.com/wp/product/kvh/).

New opportunities offered by the industrial production processes, allowed to realize bi-dimensional elements also. For instance, Oriented Strand Board (OSB) is a structural panel product realized by bonding together thin wood strands with adhesive, mainly used as infill panel into light-timber frame structures or to realize web-element in composite I-beams. Plywood fibreboards panels, instead, are made of stacked veneers organized in an odd number of layers bonded together to produce a flat sheet. (https://timberproducts.com/softwood-plywood/).

Products for one-dimensional elements				
Product	Description	Advantages	Disadvantages	
Solid wood	Solid wood	High strength	Dimensional limits	
https://royomartin.com/product/solid-wood-timbers/ (accessed on 20 March 2023)				
KVH	Solid structural sawn construction finger-jointed timber, made from softwood	High strength	Standardization of solid wood	
https://lnx.dartalegno.com/wp/product/kvh/ (accessed on 20 March 2023)				
GluLAm	Pieces of wood glued together under pressure and heat	Curved shapes Availability	Production cost	
https://www.naturallywood.com/products/glulam/ (accessed on 20 March 2023)				
I-beams	The top and bottom flanges are made with LVL, the web is made with plywood or OSB	Lightness High strength and Stiffness		
https://www.woodsolutions.com.au/wood-species/wood-products/i-beams (accessed on 20 March 2023)				

Table 1: Timber products for one-dimensional elements.

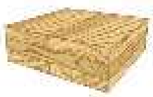
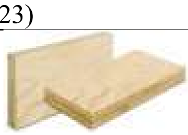
Products for both one-dimensional and two-dimensional elements				
Product	Description	Advantages	Disadvantages	
CLT	Wood panel product made from gluing together at least three layers of solid-sawn lumber	More uniform mechanical properties than wood High load bearing capacity	Production cost Renovations and changes are difficult	
https://www.naturallywood.com/products/cross-laminated-timber/ (accessed on 20 March 2023)				
LVL	Composite product manufactured from multiple thin layers of veneer that are aligned with the length of the finished lumber	High strength properties Low cost Stronger than wood	Susceptible to warm if not properly stored	
https://www.steico.com/en/solutions/product-advantages/lvl-laminated-veneer-lumber (accessed on 20 March 2023)				

Table 2: Timber products for both one-dimensional and two-dimensional elements.

As extremely versatile product, plywood is used for a wide range of structural interior and exterior applications; instead, particleboard panel is an interior-use engineered wood panel product, manufactured from wood particles. Among the engineered products, CLT surely represents the structural element most used to realize panels or beams in mid- and high-rise timber buildings in the last years [14]. CLT was introduced in Austria about thirty years ago, and its success is mainly due to (*i*) strength and stiffness both in-plane and out-of-plane, (*ii*) high dimensional stability, (*iii*) elevated in-plane isotropic strength and stiffness with respect to sawn timber, (*iv*) high speed of installation; and (*v*) the environmental benefits compared to other construction materials like steel, concrete and masonry [15,16]. CLT, and in general mass timber products, can be made from both softwoods or hardwoods timber species if engineered properly, but construction-grade softwoods such as spruce, pine, and fir are commonly employed [17].

Products for two-dimensional elements				
Product	Description	Advantages	Disadvantages	
OSB	Thin wood strands disposed in crosshatch orientation bonded together with adhesive	Cheap with respect plywood Uniform mechanical properties	Prone to retaining moisture that can result in the swelling of the board's edges It doesn't look very nice	
https://noyekplywood.co.uk/products/osb-board/ (accessed on 20 March 2023)				
Plywood	Strong panel made by thin veneers pressed together in perpendicular layers	Cheap with respect solid wood No susceptible to water damage Uniform strength	Difficult to cut	
https://timberproducts.com/softwood-plywood/ (accessed on 20 March 2023)				
Fibreboard	Wallboard made of wood chips, plant fibres, softwood flakes	Thermal insulation Light weight and easy to handle	Weaker than wood	
https://www.floorsave.co.uk/blog/fibreboard/ (accessed on 20 March 2023)				
LSL	Panels made of dried and graded wood veneers, strands or flakes that are layered upon one another and bonded together with a moisture-resistant adhesive	Low cost Stronger than wood	It doesn't look very nice	
https://www.naturallywood.com/products/laminated-strand-lumber/ (accessed on 20 March 2023)				
NLT	Structural elements realized by dimension lumber stacked together on its edge and fastened together with nails	Easily to fabricate	Once nailed, there is no possibility for rearrangement of timber panels	
https://wbdg.org/ (accessed on 20 March 2023)				
DLT	It is an evolution of NLT, with the inclusion of wooden dowels, used to replace the nails or adhesives	Flexible in terms of attachment and construction	Hardwood fasteners or dowels lose their stiffness over time	
https://www.naturallywood.com/products/dowel-laminated-timber/ (accessed on 20 March 2023)				

Table 3: Timber products for two-dimensional elements.

With regards to LVL, which is used both for two- or one-dimensional elements, it is made of dried and graded wood veneers, strands or flakes that are layered upon one another and bonded together with a moisture resistant adhesive [18]. Similarly, Solid Wood Panels (SWP) are made with timber boards glued on the edges and, if multi-layered, glued also on the upper and bottom surfaces. Laminated Strand Lumber (LSL) instead is another product similar to LVL; the difference is that it is made of flakes in lieu of layers of veneers, which are bonded together employing heat and adhesives (https://www.naturallywood.com/products/laminated-strand-lumber/). Literature studies highlighted (experimentally) the benefit in employing LSL with respect CLT in terms of bending properties [19].

Among the mass timber products, Nail-Laminated Timber (NLT) and Dowel-Laminated Timber (DLT) should be mentioned too. NLT and DLT, whose concept is dated back to the renaissance, consist of single lamellae superimposed one each other and mechanically fastened together with nails (or screws) or by hardwood timber dowels, respectively. The lamellae are disposed with its base in vertical direction and are used to realize floors mainly, also in union with a concrete slab on the top [4].

Among engineered wood products, it is interesting to mention composite elements, such as wood I-beams, light beams realized by gluing LVL flanges and plywood or OSB webs (helpful to provides high strength and stiffness thanks to the I-configuration) (https://www.woodsolutions.com.au/wood-species/wood-products/i-beams).

2.2 Buildings

In the last two decades, different factors lead to a global increase in the construction of mid- and high-rise multi-storey timber buildings: new developments in both engineering and timber manufacturing, and, overall, the ever growing need to reduce the environmental impact [20].

Until few years ago, low-rise timber buildings made with one-, two- or three-storey light-timber frame or log-haus buildings were mainly realized, while only in the last decades CLT buildings were introduced [21, 22]. Nevertheless, the recent introduction of hybrid systems, which couple timber elements with concrete or steel ones, leads the construction of mid- and high-rise timber-based buildings in seismic prone area too [23]. Indeed, the term high-rise building is not yet standardised for timber buildings but in literature it is suggest considering high-rise constructions when surpassing 10 floors or 25 meters high [22]. In Europe, the first example of high-rise timber building is the 14-storey Treet building in Bergen built in 2014 in Norway [22], completely realized with timber elements Figure 1 (a). In particular, the main structural system is composed by a glu-lam truss, which takes inspiration from contemporary bridge design, while the cellular units are realized by assembling prefabricated CLT modules and framework in laminated timber. It should be emphasised that this building is located in a low seismic area, this has make possible to realize the structure entirely with timber.

The first mid-rise European timber building is the E3 building built in Berlin in 2007 (Figure 1 (b)), designed by architects Kaden and Klingbeil. It is a seven-storey timber structure realized with glu-lam frame and CLT timber panels for walls, and equipped with two concrete cores; instead, the horizontal structures are realized with timber-concrete composite floors [24]. In 2013, the largest CLT residential complex was realized in low-seismic prone area in Milan (Italy), the Social Housing in via Cenni (Figure 1 (c)). The complex is divided into four timber towers of 27 meters high, connected between them by several two-storey linear buildings.

In Switzerland, timber high-rise buildings that reaches a height of 30 m have been realized. The first two buildings are the Suurstoffi S22 (Figure 1 (d)) completed in 2018 and the Arbo (Figure 1 (e)) completed in 2019, having 10 and 15 floors respectively. In particular, the Suurstoffi S22 is an hybrid building characterized by a concrete core, first floor in concrete, and the higher floors are provided by structural elements in laminated timber. The Arbo is a 60-storeys timber-hybrid building provided with reinforced concrete cores, frame is realized with elements in LVL and GluLam and the floors are in composite timber-concrete elements [25].

The high structural performances provided by hybrid timber buildings, lead to several design proposal aiming to overcome the height limits. Just some European example will be highlighted. Arup Group Limited proposed a 21-storey, 73 m high, tall timber building in Amstelkwartier, Netherland, i.e. the tallest timber building in the country, and further one of the tallest in the world upon completion; it is composed by internal CLT load bearing walls and CLT panels in the facades, while the ground and first floor are made of concrete. To date, two hybrid solutions have been explored during the design phase: a concrete-timber hybrid lateral stability system and a steel-timber hybrid one; after the preliminary analysis, the first solution has been chosen. [26]. Anders Berensson Architects proposed the Tratoppen building (Figure 1 (f)), a 40-story timber building to be built in Stockholm, made in laminated timber from the sixth-floor ad made of concrete for the firts floors. Finally, the Department of Architecture at Cambridge University, conceptually designed a 300 m high high-rise timber building in London, England [27], provided by timber mega-diagonals (Figure 1 (g)).

Coming out of Europe, a pioneering hybrid timber building is the 53 m tall Brock Commons Tallwood House in Vancouver (Figure 1 (h)), Canada [26], an 18-story hybrid mass timber residence at the University of British Columbia. Also in this case, 17 storeys are realized in mass timber elements, upon a concrete podium and two concrete stirs cores; the floor structure is made of CLT panels supported by Glulam columns, while the roof is made of steel beams and metal decking (https://www.thinkwood.com/construction-projects/brock-commons-tallwood-house). Ever in Canada, Michael Green and Eric Karsh proposed a 30-story hybrid tall mass-timber building known as “Finding the Forest through the Trees” [27], designed with 3 CLT panels connected by hinged steel beams (Figure 1 (i)). In the USA, the SOM (Skidmore, Owings and Merrill) proposed a design of a 42-story hybrid tall timber building, presented at the 2016 Mass Timber Conference in Portland, in which discuss the great benefits in terms of combining wood, concrete and steel in order to achieve highly efficient buildings with a reduced carbon footprint with respect the same building realized in concrete (https://www.ingenio-web.it/articoli/som-realizza-il-timber-tower-research-project/).

The most diffuse structural system for low-rise timber buildings in Europe is made of Cross Laminated Timber (CLT) walls connected to each other and to the foundation with thin-steel plates nailed to timber panels and anchored in foundation by means of steel anchors [7, 9, 30]. Since the timber panels cannot provide a ductile behaviour, they should work in the elastic field also during a seismic event, meaning that the energy dissipation is mainly entrusted to steel connectors, which, therefore, can be severely damaged after a seismic event. In this context, low-damage rocking systems, firstly introduced in New Zealand [31], are today studied also in Europe as an alternative to traditional CLT buildings above-described.

As advantage, post-tensioned walls entrust the energy dissipation to steel dampers, easily replaceable after a seismic event, while the re-centering contribution is provided by post-tensioned bars inserted in ad hoc cavities in the CLT walls [32, 33, 34].

In order to increase the sustainability of post-tensioned rocking dissipative solutions, these are also recently investigated by Lu et al. [32] employing Cross-Laminated Bamboo (CLB) panels instead of timber ones. In the proposed system, an innovative dissipation damper is also proposed, composed by friction dampers disposed at the lower corners of the walls, equipped with steel bars orthogonal to the friction plates, which provide dissipation energy through bending deformation.

(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 1: Timber-based buildings: (a) Treet building [28]; (b) E3 building - available online: https://www.world-constructionnetwork.com/projects/e3-leaf/ (accessed on 03 March 2023); (c) Social Housing - available online: http://www.rossiprodi.it/?project=social-housing-via-cenni-2 (accessed on 09 March 2023); (d) Suurstoffi S22 - available online https://burkardmeyer.ch/projekte/suurstoffi-22-risch-rotkreuz/ (accessed on 03 March 2023); (e) Arbo - available online http://www.skyscrapercentre.com/building/arbo-cabral/37225 (accessed on 07 March 2023); (f) Tratoppen building - available online https://www.skyscrapercenter.com/building/tratoppen/24866; (accessed on 07 March 2023); (g) 300 m tall buildings - available online https://plparchitecture.com/oakwood-timber-tower-london-uk/ (accessed on 07 March 2023); (h) Brock Commons Tallwood House in Vancouver available online https://www.thinkwood.com/construction-projects/brock-commons-tallwood-house (accessed on 07 March 2023); (i) Finding the Forest through the Trees [29]).

3 TIMBER-BASED SOLUTIONS FOR SEISMIC AND ENERGETIC RETROFIT OF EXISTING BUILDINGS

3.1 Brief state of the art

Timber-based solutions for retrofitting existing buildings can be considered a novel topic, either in research field and engineering practice. Literature overview remarks that most of the scientific works have been developed in the last few years substantially, while applications to real buildings are not still available (at least in the authors knowledge).

Table 4 reports a summary of some of the literature papers available on this topic, focusing on those investigating the effectiveness of specific techniques of interventions only. In addition to timber products, the Table reports the investigated aspects (e.g., seismic, energetic, or both), modes of applications (as endo- or exoskeletons) and a brief description of the interventions from structural point of view.

By looking at Table 4, some considerations arise: *a*) the great part of the research are developed in southern Europe (and in particular in Italy), this probably because the problem of updating existing buildings is particularly felt in seismic-prone areas; *b*) a large use of CLT panels as structural timber products can be observed, this is the reason of its high structural and energetic performant behavior.

Due to the great variety of the seismic-resistant interventions suitable with timber products, a classification in *exoskeletons* or *endoskeletons* appears necessary and useful for practical purposes: in the first case the retrofitting system is applied from outside of the building, while in the second one from inside. Such nomenclature, already used in Di Lorenzo et al. [38] for additional systems made with steel, has been declined to the case of timber-based systems [12]. Basically, the latter identifies two- or three-dimensional parallel or orthogonal additional skeletons applied to masonry or RC buildings. With respect to endoskeletons, exoskeletons are systems particularly beneficial in terms of monetary losses, damage reduction (to structural and nonstructural component) due to the operative working phases, and low invasiveness of interventions. Thus, they are particularly suitable in case of strategics structures- such as hospitals, police stations, first aided associations etc. – because no interruption of activities cause.

3.2 General features

Europe, and in particular the Mediterranean basin area, is constituted by significant percentage of old and vulnerable buildings stock made with no-code compliant - both from *seismic* and *energetic* points of view - masonry and reinforced concrete (RC) constructions.

Figure 2 reports the building stock distribution by age of construction in Europe provided by Ref [35]. About of 50% of the building stock is older than 50 years and many buildings in use today are hundreds of years old (i.e, historical masonry buildings). As matter of the fact, the great part of existing buildings has been constructed before the 1960s when seismic and energy regulations were very limited in Europe. About of 75% of the European buildings are inadequate to the current building standards in terms of energy efficiency [36]; whereas, about of 40% of them have been designed without particular seismic prescriptions or detailing (i.e., pre-1960).

Scholars	Timber products	Investigated aspects	Application	Brief description of the intervention
		Reinforced Concrete buildings		
Sustersic and Dujic 2012 [39]	CLT panels	S+E	EnS	CLT infill panels for RC buildings
Sandoli et al. 2021 [37]	Post-tensioned CLT walls	S	ExS	CLT walls placed parallel to RC frames
Smiroldo et al. 2021 [40]	CLT panels	S+E	EnS+ExS	CLT infill panels for RC buildings
Barbagallo et al. 2021 [43]	CLT panels	S	EnS	CLT infill panels for RC buildings equipped with friction damper connections
Aloisio et al. 2022 [41]	CLT panels	S	EnS	CLT infill panels equipped with friction connections for RC buildings
Badini et al. 2022 [42]	CLT panels	S+E	ExS	Additional orthogonal CLT walls
Li Cavoli et al. 2023 [44]	CLT panels	S	EnS	CLT infill panels for RC buildings
		Masonry buildings		
Pozza et al. 2017 [45]	CLT panels	S	EnS+ExS	Exo- or Endoskeletons parallel to masonry walls
Valluzzi et al. 2021 [46]	CLT panels	S+E	ExS	CLT panels which envelope the buildings
Cassol et al. 2021 [50]	Vertical elements	S	EnD	Interior strong-backs made with vertical timber elements connected to masonry walls
Miglietta et al. 2021 [48]	Light-timber frame	S	EnS	Light-timber frame to reinforce masonry walls
Iuorio et al. 2021 [49]	OSB panels	S	ExS	OSB panels to prevent out-of-plane of masonry walls

Legend: S= seismic, E=energetic, EnS=endoskeleton, ExS= esoskeleton

Table 4. Summary of some of the literature papers on timber-based solutions for retrofitting existing buildings.

With regard to energy efficiency, consumptions associated to spaces heating is the most significant contribution (about 60-80% of the total employed energy - https://ec.europa.eu/energy/eu-buildings-factsheets_en), meaning that the skins of the buildings are inadequate to limit heat dispersions. Concerning the seismic aspects, buildings erected before 1960s rarely are designed according to seismic prescriptions or detailing, while those erected in the period 1960-1990 often observed limited seismic rules.

Fortunately, the awareness of the seismic risk and of the climate change - to which the Covid-19 pandemic has gravely added - has motivated massive financial measures to be applied around the strategic axes of digitalization and innovation, ecological transition and social inclusion. The Next Generation EU programme, released by the European Union in the aftermath of Covid-19 pandemic, has allocated funds devoted to seismic and energetic retrofitting of existing buildings.

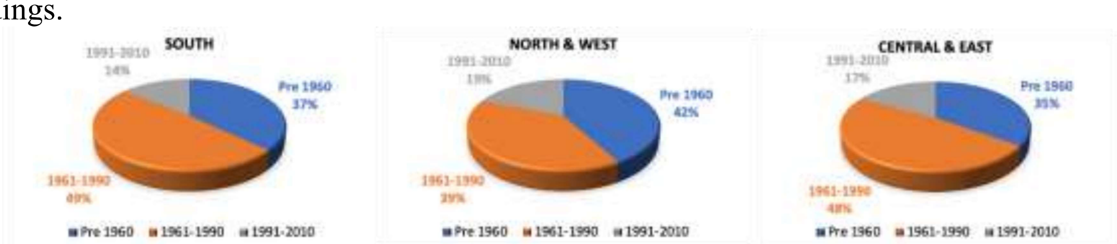


Figure 2. Age of construction of the building stock in Europe

In this framework, timber engineering has taken serious advancements in the research field introducing innovative integrated seismic and energetic retrofitting solutions for existing buildings. This has been strongly endorsed since the introduction of the engineered timber products (Glue-Lam, CLT, LVL, KVH, etc.) which represent an optimal alternative to traditional techniques of interventions. The main benefits related to the use of such products are (*i*) enhancement of the structural safety of the constructions against earthquakes (or other natural or man-made hazards) because increasing global shear capacity, stiffness and ductility of the retrofitted building; (*ii*) reduction of energetic consumption through the introduction of insulating systems of the perimetral skin of the buildings, (*iii*) the eco-sustainability of the interventions, due to natural intrinsic properties of wood material [37].

3.3 Intervention for RC buildings

Additional exo- or endoskeletons are adopted to improve the overall performances of existing RC buildings. Among the various timber engineered products, CLT panels are those frequently adopted in the scientific papers: due to their multi-layered configuration and intrinsic material properties, CLT can integrate seismic and energetic performance [14]. Some of the solutions, selected among the paper listed in Table 4, are discussed in the following. Following to 2012, where one of the pioneering studies was introduced by Sustersic and Dujic [39], a period of inactivity has characterized this research on this topic. A renewed interest on the potentiality offered by timber-based systems for retrofitting existing systems arise in the last few two/three years only. In 2021, Smiroldo et al. [40] proposed the use of CLT as infilled panels applied both from inside (endoskeleton) or from outside (exoskeleton) to existing RC framed buildings. Existing infill masonry are not demolished and CLT walls are connected to masonry by means of dry steel connectors. Inside the system, insulating layers made with wood fibers and polyurethane are also incorporated. Figure 3 reports the image of the system applied from outside of the building and the comparison among the pushover curves referred to as built and retrofitted RC frame. In the same image, the computation of the reduction energy consumption in the case of intervention made from outside or inside are indicated, in comparison with the un-retrofitted configuration.

In Figure 4, instead, is represented the reinforcing system proposed by Aloisio et al. [41], which consists of infill CLT panels connected to existing frames by means of asymmetric friction dampers (named with e-CLT). The Figure also compares the cyclic behavior of bare frame, infilled masonry RC frame and the e-CLT system: the introduction of CLT panel implies a strength reduction with respect the infill masonry frame but a significant increase in energy dissipation.

Sandoli et al. [37] proposed and investigated the potential offered by additional external post-tensioned CLT rocking walls applied to RC buildings by means of numerical analyses. CLT walls are connected to the existing frame through high-diameters steel connectors placed in the beam-to-column intersections at each story and in foundation through the post-tensioned cable (and shear key). Contrary to the case of infill CLT panels, an own foundation system (or an enlargement of that existing) devoted to withstanding the rocking behavior of timber walls is required in case of post-tensioned walls. The effectiveness of the system has been studied with reference to a real existing substandard six-storey RC building (designed for gravity loads only in Italy in 1960s) and analyzed through nonlinear static analyses.

Bandini et al. 2022 [42], instead proposed an integrated system able to join the enhancement of seismic and energetic performance with the need/opportunity of introducing additional spaces to existing RC buildings. The additional system consists of CLT-resisting walls inserted in the plane perpendicular to the external facades, connected to CLT slabs. Connection to foundation and existing structure is made with traditional hold-downs and angle brackets; horizontal slabs are connected by means post-tensioned system. The structural performances of the system have been assessed by means of linear dynamic and nonlinear static analyses.

Result outcomes obtained either in Refs. [37] and [42] are the same, and summarized as follows: additive CLT external walls provide significant increases of strength and stiffness with respect to the existing structure; CLT walls are able to distribute the deformation demand along the elevation of the RC frames, changing the collapse mechanisms from local (brittle) mechanisms at ground story to mix collapse mechanisms which involve higher seismic energy dissipation; minimum or null damage into CLT walls is expected.

Nevertheless, other interesting studies have been conducted by Barbagallo et al. [43] which proposed infill CLT wall connected to existing structure by means of friction damper and by Li Cavoli et al. [44] which proposed infill CLT panels connected to existing RC frame through classic angle-brackets nailed to the panels a dowelled to the frame or with steel plated connected to CLT panels with high ductile dowels and dowelled to the frame.

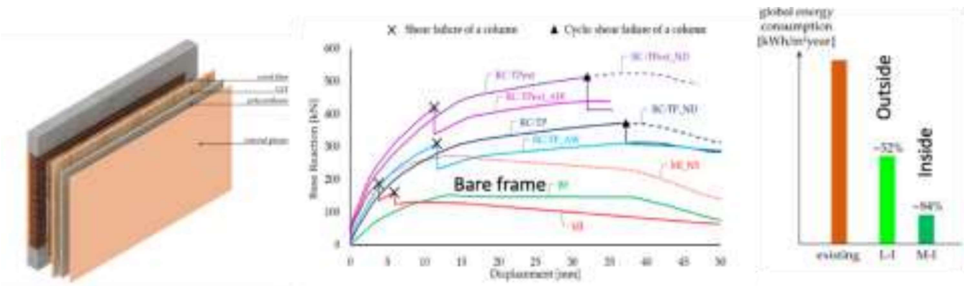


Figure 3: Retrofit solution proposed by Smiroldo et al. 2021 [40].

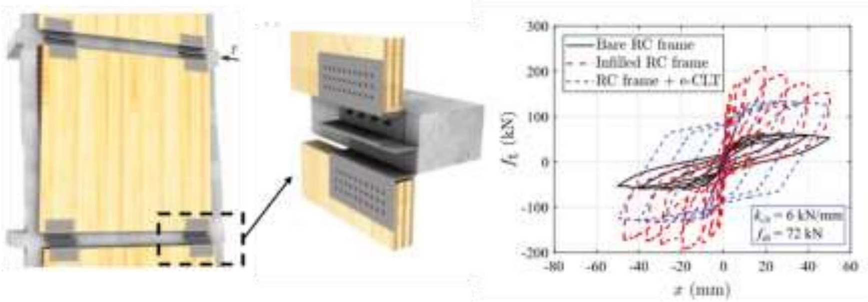


Figure 4: Retrofit solution proposed by Aloisio et al. 2022 [41].

3.4 Interventions for masonry buildings

Masonry buildings represent the structural typology most recurrent in the inner areas of Europe and in the historical centers of the most populated cities. Being, in most cases, buildings designed with lack of seismic or energetic prescriptions, integrated retrofitting interventions are crucial to reduce economic losses due to seismic damage or to reduce carbon emissions. In the perspective of seismic strengthening, retrofit solutions devoted to withstanding out-of-plane or in-plane mechanisms - often integrated with energetic solutions – are available in literature.

One of the first solution was proposed in Pozza et al. 2017 [45]. They studied, through experimental tests and numerical analyses, the effectiveness of CLT panels used as exo-or endo-skeleton to improve the seismic structural behavior (in- and out-of-plane) of masonry walls (Figure 5a). Whereas the thermal aspects have not been studied again. In Figure 5b is reported a comparison between the cyclic tests conducted on a single masonry panel unreinforced and reinforced with a single CLT panel. Comparing results of the unreinforced and reinforced walls it is possible to state that the retrofit technique induces: no increase in terms of elastic stiffness, increase of post-elastic stiffness; negligible variation of the yielding point, significant increase of the peak force, significant increase of the displacement capacity and therefore of the ductility, since the yielding condition does not vary.

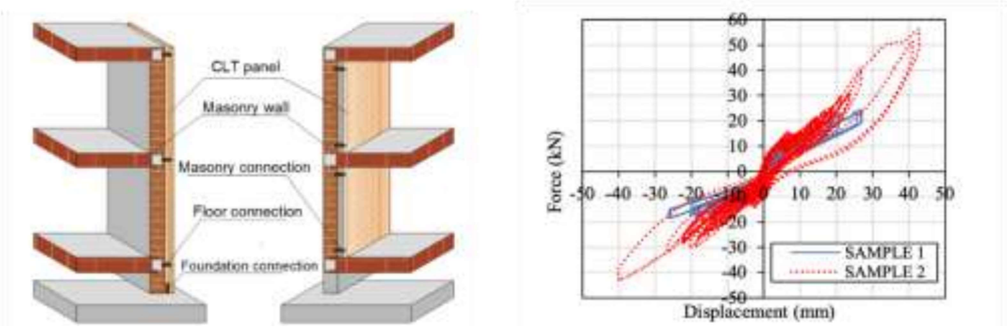
Valluzzi et al. [46] presented a valuable integrated structural and energy solution based on the concept of 'nested building' (Figure 6): it enables to retrofit and reuse existing buildings by (i) preserving the external envelope, (ii) removing the internal elements, and (iii) inserting a new inner coat layer with high structural and energetic performances. The efficacy of such solution has been analyzed from seismic and energetic points of view. Stone and hollow clay brick masonry has been considered as base material, reinforced with CLT panels provided with additional insulating material layers: the reinforcing system is connected to existing walls by means of steel bars injected in the masonry walls. It has been studied the seismic behavior, both in-plane and out-of-plane, of the reinforced systems. The higher stiffness of the panels reduced about 30% the in-plane displacement of the walls, while the coupling in the OOP direction was not fully reached even with the minimum spacing of the connectors. Thus, the CLT-stone masonry connection may not be sufficient to exclude OOP mechanisms and a careful evaluation of construction details able to ensure the connection of masonry walls at floor levels is needed.

The hygrothermal performance resulted different in the case of stone masonry and hollows clay-brick masonry. In the first case a significant reduction in both the steady and the periodic thermal transmittance reached values of 0.278 W/m^{2}K and 0.007 W/m^{2}K, while in the second values of 0.235 W/m^{2}K and 0.006 W/m^{2}K, respectively; in both cases, the achieved values are lower than that provided by the Italian code [47].

Iuorio and Dauda [48] investigated the possibility to use oriented strand boards (OSB) panels to improve the out-of-plane performance of brick masonry walls. They performed both experimental tests and numerical analyses (with reference to a four-point bending test) aimed at characterizing the structural behavior of the proposed systems.

Miglietta et al [49] tested on shake-table a two-storey masonry building (the first unreinforced and the second reinforced) to assess the effectiveness of a retrofit solution made with light timber frame systems. It is an innovative sustainable, lightweight, reversible, and cost-effective technique, which could be extensively applied to actual buildings. Timber frames were connected to the interior surface of the masonry walls and completed by oriented strands boards nailed to them. Moreover, the second-floor timber diaphragm was stiffened and strengthened by a layer of oriented-strand boards, nailed to the existing joists and to additional blocking elements through the existing planks. Test result highlighted that the retrofit was effective at enhancing the walls in-plane and out-of-plane capacities, also improving the connections between structural elements, and thus inducing a global box-type behavior on the retrofitted building, with full exploitation of the in-plane capacities of all masonry piers. Despite changing the failure mechanism and the overall lateral resistance of the building, the retrofit application did not affect the initial fundamental period of 0.17 s, thanks to its small mass and stiffness compared to those of the masonry structure.

Cassol et al. [50], instead, proposed to prevent put-of plane of masonry walls through vertical timber elements (strong-backs) placed as endoskeleton, connected to masonry using mechanical screws or bolts. The out-of-plane behavior of as-built and retrofitted masonry walls was investigated by conducting full scale static airbag tests. The walls were subjected to semi-cyclic out-of-plane loading through the application of uniformly distributed loads, using inflated airbags in order to simulate the self-weight inertia force induced by an earthquake. A simplified numerical model to predict the response of the masonry wall retrofitted using timber strong-backs was developed using the finite element software SAP2000. As main result, the capacity of the retrofitted walls was found to be > 3.5 times that of the URM walls when the strong-back is on the compression side and > 5.6 times when the strong-back is on the tension side.



a) b)

Figure 5: Retrofit solution proposed by Pozza et al. 2017 [45].

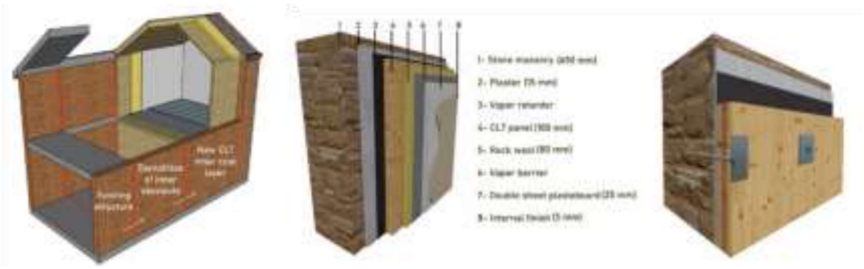


Figure 6: Retrofit solution proposed by Valluzzi et al. 2021 [46].

4 PROSPECTIVE OF SHORT CHAINS TO IMPROVE LIFE CYCLE OF MATERIAL AND ITS IMPACT ON ENVIRONMENT

Sustainable constructions embraces several aspects, such as design and management of buildings and constructed assets, choice of materials, building performance as well as interaction with urban and economic development and management. Timber as a material and as a structural system could be an ideal for a new era of construction.

One of the most favorable aspects of timber short supply chain development is the reduction of carbon emission and the carbon sequester. The built environment generates 40% of annual global CO_2 emissions. Of those total emissions, building operations are responsible for 27% annually, while building and infrastructure materials and construction (typically referred to as embodied carbon) are responsible for an additional 13% annually. So it has become crucial determining the full lifecycle impact of mass timber on carbon emissions starting from the transport of the row cut log to the amount of carbon embedded in the timber itself, where it is sequestered in buildings that could last anywhere from 50 to hundreds of years [51].

Over the past decade, there has been growing interest in mid- and high-rise buildings constructed from mass timber materials as a means to achieve greater urban density with more sustainable construction [20, 52].

A rise in the demand for wooden construction, especially for residential and commercial construction sectors along with the large amount of material required to supply the construction of tall timber buildings put the timber global supply chain under pressure and require overhauling the timber market rules.

In the last years many efforts have been addressed to exploit wooden species of short supply chain to obtain timber products also suitable for structural building [53, 54], according to the principles of the European and Italian Bioeconomy strategy (https://ec.europa.eu/research/bioeconomy/index.cfm?pg=policy) launched at 2012 aiming to accelerate the deployment of a sustainable European bioecomomy by developing a circular economy and by reducing the dependence on non-renewable resources.

Samples of this good practice are repoted in Sikora et al. [55] which analized the influence of the thickness on mechanical performance in bending and shear of Irish Sitka spruce CLT panels, Fortune and Quenneville [56] who analized the behavior of CLT panels realized by using locally grown Radiata Pine and Concu et al. (2018) [57] and Fragiacomo et al. (2015) [58] respectively examinated the behavior of Italian Marine Pine in Sardinia for the CLT short procurement chain in the Mediterranean area. Short supply Italian beech in homogeneous and hybrid configuration with Calabrian Corsican pinewas investigated by Sciomenta et al. (2021) [59] for the manufactoring of CLT panel as well for the production of glulam beams [60] (Figure 7). These tests aimed to prove the goodness for structural applications of one of the most widespread hardwood species in Italy.

Recently, also national codes have stepped forward to enhance short supply chain products. The New Zeeland Standard NZS AS 1720.1:2022 (ICS Codes, 2022) [61] has included information specifically for New Zealand-grown timber such as stress grade, density, tension, bending, compression, modulus of elasticity, and load-bearing capacity. Consideration for New Zealand-grown timber is especially important since timber properties rely on not only the species grown, but where it is grown, hence the need for modification of the AS and measures to accommodate.

Figure 7. Short supply beech CLT panel under out plane load [59]

5 CODES AND GUIDELINES

The growing interest in wooden structures is also evidenced by the updates of the codes deriving from various part of the world. At European level, the two main documents for the design of timber constructions are Eurocode 5 [62] and Eurocode 8 [63] - the first dedicated to basic of design of structural members and connections, and the second to the design of seismic-resistant structures – both updating. In line with the Eurocodes, the Technical Document CNR-DT 206-R1/ 2018 (Instructions for the Design, Execution and Control of Timber Structures - has been recently update in Italy and represent (probably) one of the most advanced documents oriented to seismic design of timber buildings available in Europe. In its first version the Document included both rules for check and design single timber member or subassemblies (such as arches, diaphragms, braces etc.) only, while in 2018 a revised version was released containing seismic design rules for timber buildings based on capacity deign [8].

The Eurocode 8 provides harmonized technical rules to achieve uniform levels of safety in the field of seismic design of structures. In the current version, only six pages of specific rules for new timber buildings are provided in Chapter 8 of EN 1998-1: General rules, seismic actions and rules for buildings while, no specific chapters on existing timber buildings are defined in EN 1998-3: Assessment and retrofitting of buildings.

In the next generation of Eurocode 8 relevant updates will be provided. It was proposed to subdivide Part 1 in Part 1-1: General rules and seismic action and Part 1-2- Rules for new buildings (Chapter 13: Timber) respectively. This latter Chapter will be extended from 6 to 40 pages with novelties concerning different aspects. At first, some new wood-based panels with related rules will be introduced as the Oriented Strain Boards (OSB), the Gypsum Fibre board (FF) and in particular, the Cross Laminated Timber (CLT). Will be revised the definition of structural types according to their behavior under horizontal seismic actions in ten different typologies.

New safety format for seismic verifications will be specified, in particular the previous dissipative classes named with Low Ductility Class (DCL), Medium Ductility Class (DCM) and High Ductility Class (DCH) will be respectively replaced with DC1 (non-dissipative), DC2 (medium dissipative) and DC3 (highly dissipative) classes. For the verification of DC2 and DC3 in SD Limit State, the design strength of dissipative zones will be calculated by introducing: *i)* the k_{deg} strength reduction factor due to cyclic degradation, assumed to be equal to 0.8 when no experimental results are available or estimated experimentally as ratio between $F_{1,cycle}$ (EN12512) / $F_{monotonic}$ (EN26891); *ii)* the values of γ_m=1 as those given in EN 1995-1-1:2004 and A1:2008 for accidental situations.

Another novelty will regard the new definition of behavior factors q according to EN1998-1-1. It will be given as product of three components: q_S the over-strength component introduced in the design phase (1.5 material independent), q_R the over-strength component due to the redistribution of seismic action in redundant structures; q_D the deformation capacity and energy dissipation component. For each of the ten structural types will be specified: for design in DC1, the q factor and maximum value of the seismic action index S_δ; for the design in DC2 and DC3 the values of q, and/or q_R and q_D when applicable.

Moreover, new ductility rules for dissipative zones will be specified. The dissipative zones for each structural type designed in DC2 and DC3 should be located in joints and connections where the energy dissipation should take place by flexural yielding of metal fasteners, whereas the timber members themselves should be designed to behave elastically.

The values of ductility are specified for DC2 and DC3 and for each dissipative zone of each structural type (i.e., CLT structures: shear walls, hold-downs, screwed wall panel-to-panel joints).

Another update will concern the capacity design and the specification of novel over-strength factors. These latter will be specified for capacity design at connection and 2D/3D nailing plate level or at wall and building level considering the different possible brittle/non-dissipative failure modes occurring.

The last novelty concerns the introduction of detailing rules for the correct design of all the structural types.

6 CONCLUSIONS

This paper reports a state of the art on recent developments concerning the use of structural timber in Europe, focusing on new single products, structural systems for buildings, new solution for seismic and energetic retrofit of existing masonry and RC buildings, aspects related to short chain and life cycle assessment, and last advancements for codes and guidelines.

Due to the potentials offered by raw material - related to structural and environmental aspects - timber constructions have become more and more attractive over the years. The ever-increasing demand in terms of quantity and performance of timber-based products led to great technological innovations and research advancements.

One of the most evident results is the global increase of mid- and high-rise multi-storey timber building, which design, combined with the diffusion of some products for structural purposes such as CLT, required an update of the regulations (i.e., EC8).

The potential of timber is not limited only to new constructions but also extends to existing buildings. The Europe, and in particular the Mediterranean basin area, is constituted by significant percentage of old and vulnerable buildings both under the energetic and seismic point of view. In this framework, timber engineering has taken serious advancements in the research field introducing innovative integrated seismic and energetic retrofitting solutions for existing buildings.

To conclude, the environmental benefits of wood are immense and up to now not maximized. This is the reason why several scientific studies have been carried to investigate the structural performances of short supply timber to produce novel engineered wood products.

REFERENCES

[1] Swedish Wood. *The CLT Handbook-CLT Structures*, Fact and Planning; Swedish Wood: Stockholm, Sweden, 2019.

[2] M. Dzian, H. Palus, J. Parobek . Global Trends Affecting the EU Timber Trade. *Proc of Digitalisation and circular economy: forestry and forestry based industry implications*, Bulgaria, 297-301, 2019.

[3] H. Svatoš-Ražnjevi´c, L. Orozco, Menges, A. Advanced Timber Construction Industry: A Review of 350 Multi-Storey Timber Projects from 2000–2021. *Buildings*, **12**, 12, 404, 2022. https://doi.org/ 10.3390/buildings12040404.

[4] M. Gong, Meng. "Lumber-Based Mass Timber Products in Construction." *Timber Buildings and Sustainability*, 2019. IntechOpen. doi:10.5772/intechopen.85808.

[5] V. Salvadori. Multi-Storey Timber-Based Buildings: An International Survey of Case-Studies with Five or More Storeys Over the Last Twenty Years; *Technische Universität Wien: Vienna*, Austria, 2021.

[6] U. Kuhlmann, J. Schänzlin. A Timber-Concrete Composite Slab System for Use in Tall Buildings, *Structural Engineering International*, **18** (2), 2008. DOI: 10.2749/101686608784218707

[7] A. Sandoli, C. D'Ambra, C. Ceraldi, B. Calderoni, A. Prota. Sustainable Cross-Laminated Timber Structures in a Seismic Area: Overview and Future Trends. *Applied Sciences*, **11**(5), 2078, 2021.

[8] B. Faggiano, A. Sandoli, G. Iovane, M. Fragiacomo et al. The Italian instructions for the design, execution and control of timber constructions (CNR-DT 206 R1/2018). *Eng Struct*, **253**, 113753, 2022,.

[9] M. Follesa, M. Fragiacomo, D. Casagrande, R. Tomasi, M. Piazza, D. Vassallo, D. Canetti, S. Rossi. The new provisioned for the seismic design of timber buildings in Europe, *Eng. Struct*, **168**, 736–747, 2018.

[10] M. Busselli, D. Cassol, A. Prada, I. Giongo. Timber Based Integrated Techniques to Improve Energy Efficiency and Seismic Behaviour of Existing Masonry Buildings. *Sustainability*, **13**, 10379, 2021.

[11] G. Iovane, A. Sandoli, D. Marranzini, R. Landolfo, A. Prota, B. Faggiano. Timber based systems for the seismic and energetic retrofit of existing structures. *Proc Struct Integrity* **44**,1870-1876, 2023.

[12] F. Smiroldo, I. Giongo, M. Piazza. Use of timber panels to reduce the seismic vulnerability of concrete frame structures. *Eng Struct*, **244**(2),112797, 2021.

[13] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel. Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, **74**(3), 2016 https://doi.org/10.1007/s00107-015-0999-5

[14] M. Jeleč, D. Varevac, V. Rajčić: Cross-laminated timber (CLT) – a state of the art report, *GRAĐEVINAR,* **70**(2), 75-95, 2018. doi: https://doi.org/10.14256/JCE.2071.2017

[15] J.W.G. Van De Kuilen, A. Ceccotti, Z. Xia, M. He,Very Tall Wooden Buildings with Cross Laminated Timber, *Procedia Engineering*, **14**, 1621-1628, 2011, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2011.07.204

[16] J. Comnick, L. Rogers, K. Wheiler. Increasing Mass Timber Consumption in the U.S. and Sustainable Timber Supply. *Sustainability*, **14**, 381, 2022. https://doi.org/10.3390/su14010381

[17] CLT Handbook: *Cross Laminated Timber; FP Innovation Special Publication* SP-529E; U.S. Edition: St. Jean Pointe-Claire, QC, Canada, 2013.

[18] Z. Wang, M. Gong, Y.H. Chui. Mechanical properties of laminated strand lumber and hybrid cross-laminated timber. *Constr Build Mater* **101**, 622-7, 2015. https://doi.org/10.1016/J.CONBUILDMAT.2015.10.035.

[19] S. Breneman, L. Podesto. Timber Skyline: A Review of Structural Systems for High-Rise Wood Structures. *2013 SEAOC Convention Proceedings*. San Diego, September 2013, 2013.

[20] M. Jeleč, D. Varevac, V. Rajčić: Cross-laminated timber (CLT) – a state of the art report, *GRAĐEVINAR,* **70** (2), 75-95, 2018. doi: https://doi.org/10.14256/JCE.2071.2017

[21] V.Ž. Leskovar, M. Premrov. *A Review of Architectural and Structural Design Typologies of Multi-Storey Timber Buildings in Europe*, **12**, 2021, https://doi.org/10.3390/F12060757.

[22] A. Iqbal. Development in tall wood buildings and hybrid buildings and environmental impacts. *Sustainability*, **13**, 11881, 2021.

[23] S. Lehmann. Sustainable construction for urban infill development using engineered massive wood panel systems. *Sustainability*, **4**, 2707–42, 2012. https://doi.org/10.3390/SU4102707.

[24] R. Jockwer, P. Grönquist, A. Frangi. Long-term deformation behaviour of timber columns: Monitoring of a tall timber building in Switzerland. *Eng Struct*, **234**, 1118552021; 2016:. https://doi.org/10.1016/J.ENGSTRUCT.2021.111855.

[25] R. Verhaegh, M. Vola, J. de Jong, Haut - A 21-storey Tall Timber Residential Building. International Journal of High-Rise, *Building*, **9**(3), 213-220, 2020.

[26] M.A. Bezabeh, G.T. Bitsuamlak, M. Popovski, S. Tesfamariam. Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part I - structural design and wind tunnel testing. *J Wind Eng Ind Aerodyn*, **181**, 85–103, 2018;. https://doi.org/10.1016/J.JWEIA.2018.08.012.

[27] A. Sandoli, D. Moroder, S. Pampanin, B. Calderoni. Simplified analytical models for coupled CLT walls. *Proc. Of the World Conf on Timb Eng*, Wien, 2016.

[28] S. Tulebekova, K.A. Malo, A. Rønnquist, P. Nåvik. Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings. *Eng Struct*, **261**, 114209, 2022. https://doi.org/10.1016/J.ENGSTRUCT.2022.114209.

[29] M. Fairhust, Z. Xiaoyue, T. Tannert. Nonlinear dynamic analyses of novel timber-steel hybrid system. *World Conference on Timber Engineering*, Canada, Quebec City, 10-14 August, 2014.

[30] A. Palermo, S. Pampanin, A. Buchanan, M. Newcombe. Seismic design of multi-storey buildings using laminated veneer lumber (LVL). *Proc of the NZSEE Conference*, New Zealand, Wairakei, 2005.

[31] A. Iqbal, S. Pampanin, A. Palermo, A.H. Buchanan. Performance and design of LVL walls coupled with UFP dissipaters. *J Earthq Eng* 2015. https://doi.org/10.1080/13632469.2014.987406.

[32] Y. Lu, Q. Lv, Y. Liu. Experimental and numerical study on seismic performance of CLB rocking wall with bending-friction coupled dampers. *J Build Eng*, **45**, 103622, 2022. https://doi.org/10.1016/j.jobe.2021.103622.

[33] L. Pozza, L. Benedetti, V. Tomei, B. Ferracuti, M. Zucconi, C. Mazzotti. Cyclic response of CLT Post-Tensioned Walls: Experimental and numerical investigation, *Construction and Building Materials*, **308**, 125019 ,2021.

[34] V. Tomei, M. Zucconi, B. Ferracuti. Post-tensioned rocking dissipative timber wall systems: Numerical prediction, *Journal of Building Engineering*, **66**, 105897, 2023.

[35] EU building database. An official website of the European Union. Available at: https://ec.europa.eu/energy/eu-buildings-database_en .

[36] F. Filippidou, J. Jimenez Navarro. Achieving the cost-effective energy transformation of Europe's buildings, EUR 29906 EN. *Publication office of the European Unioni, Luxemburg*, 2019.

[37] A. Sandoli, B. Calderoni, A. Prota. A displacement-based design methodology devoted to post-tensioned timber walls for seismic retrofit of an existing RC building. *Ingegneria Sismica*, **38**(2), 70-94, 2021.

[38] G. Di Lorenzo, F. Colacurcio, A. Formisano, A. Massimilla, R. Landolfo. State-of-the-art on steel exoscheletons for seismic retrofit of existing RC buildings. *Ingegneria Sismica*, **37**(1), 33-50, 2022

[39] I. Sustersic, B. Dujic. Seismic strengthening of existing buildings with cross laminated timber panels. *Proc. of World Conf on Timb Eng*, Auckland, New Zealand, 2012.

[40] F. Smiroldo, I. Paviani, I. Giono, P. Zanon, R. Albatici, M. Piazza. An integrated approach to improve seismic and energetci behaviour of RC framed buildings using timber panels. *Sustainability*, **13**, 11304, 2021.

[41] A. Aloisio, M. Pellicciari, S. Sirotti, F. Boggian, R. Tomasi. Optimization of the structural coupling between RC frames, CLT shear walls and asymmectric friction connections. *Bull of Earth Eng*, **20**, 3775-3800, 2022.

[42] L. Bandini, P. Aondio, S.J. Ott, S. Winter. Seismic Strengthening of Existing RC Buildings With External Cross-Laminated Timber (CLT) Walls Hosting an Integrated Energetic and Architectural Renovation. *Bull of Earth Eng*, **20**, 5963–6006, 2022.

[43] F. Barbagallo, G. Margani, E.M. Marino, A. Moretti, C. Tardo. Impact of retrofit of rc frames by clt panels and friction dampers. *Proc of 8th Int Conf on Comp Meth in Struct Dyn and Earth Eng (COMPDYN)*, Greece, Athens, 2021, DOI: 10.7712/120121.8636.18851

[44] D. Li Cavoli, G. D'Arenzo, M.E. Ruggeri, M. Fossetti. On the use of CLT infills to improve the lateral performance of RC frames. *Lecture Notes in Civil Eng*, 2023, DOI: 10.1007/978-3-031-21187-4_75

[45] L. Pozza, F. Evangelista, R. Scotta. CLT used as seismic strengthener for existing masonry walls. *Proc of the XVII Italian Conf on Earth Eng (ANIDIS)*, 210–220, 2017.

[46] M.R.Valluzzi, E. Saler, A. Vignato et al. Nested buildings: An innovative strategy for the integrated seismic and energy retrofit of existing masonry buildings with CLT panels. *Sustainability*, **13**(3), 118, 2021

[47] DM 26/06/2015—Italian Interministerial Decree: Application of Calculation Methods for Energy Performance and Definition of Minimum Building Requirements; *Official Gazette of the Italian Republic: Rome*, Italy, 2015. (In Italian).

[48] O. Iuorio, J.A. Dauda. Retrofitting Masonry Walls against Out-Of-Plane Loading with Timber Based Panels. *Applied Sciences*, **11**(12), 5443, 2021.

[49] M. Miglietta, N. Damiani, G. Guerrini, F. Graziotti. Full-scale shake-table tests on two unreinforced masonry cavity-wall buildings: effect of an innovative timber retrofit, *Bulletin of Earthquake Engineering*, **19**(6): 2561-2596, 2021.

[50] D. Cassol, I. Giongo, J. Ingham, D. Dizhur. Seismic out-of-plane retrofit of URM walls using timber strong-backs. *Constr. Build. Mater*, **269**, 121237, 2021.

[51] D. Roberts, The hottest new thing in sustainable building is, uh, wood, Vox Media, LLC, 15 Jan 2020, Online: https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt (accessed on 21 March 2020).

[52] Timmers M, Rogowksi B, Jacobs AT, Jones B. Mass Timber High-Rise Design Research: Museum Tower in Los Angeles Reimagined in Mass Timber. *2015 SEAOC Convention Proceedings*, Bellevue, WA. September, 2015.

[53] M. Romagnoli, M. Fragiacomo, A. Brunori, M. Follesa, and G. Scarascia Mugnozza, "Solid wood and wood based composites: The challenge of sustainability looking for a short and smart supply chain," *Lect. Notes Civ. Eng.*, **24**, 783–807, 2019, doi: 10.1007/978-3-030-03676-8_31.

[54] G. Scarascia Mugnozza, M. Romagnoli, M. Fragiacomo, M. Piazza , B. Lasserre, M. Brunetti, R. Zanuttini, M. Fioravanti, M. Marchetti, L. Todaro, M. Togni, T. Ferrante, M. Maesano, M. Nocetti, G.B. De Dato, M. Sciomenta, T. Villani. La filiera corta del legno:

un'opportunità per la bio-economia forestale in Italia. *Forest@* **18**, 64-71, 2021. doi: 10.3832/efor0052-018

[55] K.S. Sikora, D.O. McPolin, A.M. Harte. Effects of thickness of cross-laminated timber (CLT) panels made from Sitka spruce on mechanical performance in bending and shear. *Constr. Build. Mater*, **116**, 141–150, 2016

[56] A.L. Fortune, P. Quenneville. A feasibility study of New Zealand Radiata Pine crosslam, *S. Setunge*, **116**, 141-150, 2011.

[57] G. Concu, B. De Nicolo, M. Fragiacomo, N. Trulli, M. Valdes, Grading of maritime pine from Sardinia (Italy) for use in cross-laminated timber, *Proc. Inst. Civ. Eng. Constr. Mater*. **171**(1), 11–21, 2018. https://doi.org/10.1680/jcoma.16.00043.

[58] M. Fragiacomo, R. Riu, R. Scotti, Can structural timber foster short procurement chains within Mediterranean Forests? A research case in Sardinia, South-east Eur. *For.* **6**(1), 107–117, 2015. https://doi.org/10.15177/seefor.15-09.

[59] M. Sciomenta, L. Spera, C. Bedon, V. Rinaldi, M. Nocetti, M. Brunetti, M. Fragiacomo, M. Romagnoli. Mechanical characterization of novel Homogeneous Beech and hybrid Beech-Corsican Pine thin Cross-Laminated timber panels. *Constr. Build. Mater.*, **271**, 2021. doi: 10.1016/j.conbuildmat.2020.121589

[60] M. Sciomenta, Spera L., Peditto A., Ciuffetelli E., Savini F., Bedon C., Romagnoli M., M. Nocetti, M. Brunetti, M. Fragiacomo, Mechanical characterization of homogeneous and hybrid beech-Corsican pine glue-laminated timber beams, *Engineering Structures*, **264**, 114450, ISSN 0141-0296, 2022,.

[61] ICS Codes, NZS AS 1720.1:2022 Timber structures. Part 1: Design methods.

[62] EN 1995-1-1:2004 Eurocode 5: Design of Timber Structures, Part 1-1: General rules and rules for buildings.

[63] EN 1998-1:2005 Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings.