SEISMIC DESIGN OF CROSS-LAMINATED TIMBER BUILDINGS

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Wood and Fiber Science, 50(Special Issue), 2018, pp. 3-26
https://doi.org/10.22382/wfs-2018-037

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(Received February 2018)

Abstract. The increasing interest in cross-laminated timber (CLT) construction has resulted in multiple international research projects and publications covering the manufacturing and performance of CLT. Multiple regions and countries have adopted provisions for CLT into their engineering design standards and building regulations. Designing and building CLT structures, also in earthquake-prone regions is no longer a domain for early adopters, but is becoming a part of regular timber engineering practice. The increasing interest in CLT construction has resulted in multiple regions and countries adopting provisions for CLT into their engineering design standards. However, given the economic and legal differences between each region, some fundamental issues are treated differently, particularly with respect to seismic design. This article reflects the state-of-the-art on seismic design of CLT buildings including both, the global perspective and regional differences comparing the seismic design practice in Europe, Canada, the United States, New Zealand, Japan, China, and Chile.

Keywords: Seismicity, design standards, platform-type construction, ductility, connections.

INTRODUCTION

Seismicity and Seismic Design

Earthquake ground motions are caused by a relative movement of the world's tectonic plates. Seismic waves, often carrying a substantial amount of energy, are created when these plates slide along another. These waves occur deep in the Earth's crust and change their characteristics while propagating. The resulting seismic risk for structures can be traced back to an interaction between the seismicity of the region, the local ground conditions, and the dynamics characteristics of the structure (Hummel 2017).

Among the available seismic engineering design approaches, the equivalent static force–based method and the response spectrum procedure represent the most common methods. In force-based design, elastic forces are based on an initial elastic estimate of the building period combined with a design spectral acceleration for that period. Subsequently, design force levels are reduced from the elastic level by applying code-specified force reduction factors based on the ductility, damping, and overstrength of the structure. In the International Building Code (IBC 2018) and FEMA P695 (FEMA 2009), the response modification factor is defined as R; whereas in the National Building Code of Canada (NBCC) (NRC 2015), it is set equal to the product $R_d \times R_o$ where R_d is the reduction factor for ductility, and R_o is an overstrength factor.

In New Zealand, the earthquake loadings standard New Zealand Standard (NZS) 1170.5 (NZS 2004) uses the inelastic spectrum factor k_μ and the structural performance factor S_p to determine the ultimate limit state modal response spectrum from the elastic spectrum. In Europe, according to the general requirements of Eurocode 8 (EC8) (CEN 2004), the energy dissipation capacity of the seismic forces obtained from a linear analysis are divided by the behavior factor q corresponding to the associated ductility class, which accounts for the nonlinear response of the structure associated with the material, the structural system, and the design procedures. The subsequent section will discuss the seismic design approaches in Europe, Canada, the United States, New Zealand, Japan, China, and Chile in more detail.

Cross-Laminated Timber and Research on its Seismic Performance

Cross-laminated timber (CLT) was first developed in the early 1990s in Austria and Germany and ever since has been gaining popularity in structural applications, first in Europe and then worldwide (Gagnon and Pirvu 2012). CLT is a viable wood-based structural material to support the shift toward sustainable densification of urban and suburban centers. CLT panels consist of several layers of boards (from the center outward balanced in lay-up) placed orthogonally to each other (at 90°) and glued together. Such panels can then be used for wall, floor, and roof assemblies. CLT panels offer many advantages compared with traditional light-frame wood construction, most notably the fact that the cross-lamination provides improved dimensional stability and that large-scale elements can be prefabricated (Brandner et al 2016), also with large openings (Shahnewaz et al 2017).

The SOFIE project, carried out by the National Research Council (NRC) of Italy in collaboration with the National Institute for Earth Science and Disaster Prevention, Shizuoka University, the Japanese Building Research Institute, and the Center for Better Living was the most comprehensive study to quantify the seismic behavior of CLT buildings (Ceccotti and Follesa 2006; Lauriola and Sandhaas 2006; Ceccotti et al 2013). Cyclic tests were conducted on CLT walls, a pseudo-dynamic test on a one-story CLT building, and first a three-story building and subsequently a seven-story CLT building were tested on shake tables using different configurations applying multiple earthquake records. These tests allowed evaluating the performance of CLT panels and connections, and validating design assumptions regarding component and system ductility. It was observed that the overall structural behavior was mostly influenced by the performance of the connections which dissipated the seismic energy, whereas the CLT panels behaved as rigid bodies. Numerical models were developed and nonlinear time-history analyses were performed, and a q-factor of 3.0 was obtained for CLT buildings made with walls composed of more than one CLT panel of width not greater than 2.5 m connected to the other panels by means of vertical joints made with self-tapping screws. The seven-story building was designed with a q-factor of three and an importance factor of 1.5 according to EC8 (CEN 2004) and withstood all earthquake excitations without any significant damage.

In Canada, the most relevant research from a code perspective was conducted at FPInnovations (Popovski et al 2010; Gavric et al 2015; Popovski and Gavric 2015). A two-story CLT structure was tested under quasi-static monotonic and cyclic loading in two directions, one direction at a time. The building was designed following the equivalent static procedure with $R_{\mathrm{d}} = 2.0$ and $R_0 = 1.5$. Failure occurred because of combined sliding and rocking at the bottom of the first story; however, no global instabilities were detected. These force reduction factors were included as recommendations in the Canadian CLT handbook (Gagnon and Pirvu 2012).

In the United States, research efforts were led by Pei et al (2013, 2015, 2017), who first estimated the seismic modification factor for multistory CLT buildings based on numerical analyses on a six-story CLT shear wall building. The results showed that an R-factor of 4.5 could be assigned to CLT wall components when the building is designed following ASCE 7 (ASCE 2016) equivalent lateral force procedure (ELFP). Subsequently, a new seismic design approach for tall CLT platform buildings was proposed where the CLT floors are considered as the coupling elements. The analysis of a case study building indicated the potential of the proposed method; however, experimental validation is underway (van de Lindt et al 2016).

In Japan, Yasumura et al (2015) investigated a two-story CLT structure under cyclic loading designed fully elastically and showed that the elastic design procedure was conservative. Full-scale shake table tests were conducted on three- and five-story CLT buildings (Kawai et al 2016) under three-dimensional input waves of 100% and 140% of the Kobe earthquake. At the 140% ground motions level, the three story building was severely damaged; however, it did not fail. Miyake et al (2016) estimated the capacity and the required shear wall length in accordance with the Building Standard Law (BSL) of Japan and showed that the required wall quantity for the five-story CLT building was approximately two times larger than that of the three-story building. In New Zealand, Moroder et al (2018) tested a two-story posttensioned CLT Pres-Lam core wall under bidirectional quasi-static seismic loading using both standard screwed connections and steel pivotal columns with dissipative U-shaped flexural plates. Only nominal damage to the walls, wall connections, and diaphragm connections was observed after large drift demands of up to 3.5%.

DESIGN PROVISIONS IN EUROPE

Regulatory Framework in Europe

Within the framework of the European legislation, which defines the essential requirements which goods shall meet to be commercialized in the European market, the European standard bodies have the task to produce technical specifications for the different product sectors. These rules shall be followed to meet the aforementioned essential requirements. Following this philosophy, the European Union has produced a set of technical regulations, called Eurocodes, ie for structural design, with the intent to foster the free movement of engineering and construction services and products within the Union, protect the health and safety of European citizens, and promote the sustainable use of natural resources. With this intent, the Eurocodes were first issued in 1984 to be applied as an alternative within the corresponding national rules of the same technical matters. The intent was to reach a common agreement among all the member countries so that common performance criteria and general principles concerning the safety, serviceability, and durability of the different types of construction and materials could be gradually adopted, replacing, in the end, the different National regulations (European Union 2016).

The Eurocodes, which shall meet the essential requirements defined by the Construction Product Directive (mechanical and fire resistance, hygiene, health, safety and accessibility in use, noise protection, energy efficiency, and sustainability) are divided into 10 different documents which cover: basis of structural design (EC0); actions on structures (EC1); design of concrete (EC2); steel (EC3); composite steel and concrete (EC4); timber (EC5); masonry structures (EC7); aluminum structures (EC9); geotechnical design (EC7); and design, assessment, and retrofitting of structures for earthquake resistance (EC8). Each Eurocode is divided itself into a number of parts covering specific aspects which, especially for the codes related to materials, have the same numbering (1-1 Generic rules and rules for buildings, 1-2 Structural fire design, two Bridges, etc.). Following the specifications included within the Public Procurements Directive, it is mandatory that member states accept designs made according to the Eurocodes and, if the structural designer is proposing an alternative design, he/she must demonstrate that it is technically equivalent to the Eurocode solution (Dimova et al 2015).

The compliance of the common rules with the corresponding national safety levels have been left to the specification of appropriate values, the so-called Nationally Determined Parameters which can be chosen by the different state members and are published in National Annexes to the Eurocodes. National building codes are still effective within the European Union; however, because an alternative Eurocode design must be always accepted, they are all becoming very similar to Eurocodes and are expected, in the near future, to be completely replaced by Eurocodes with the corresponding National Annexes.

The construction product certification can be performed according to the technical requirements provided by harmonized European standards or, for those products which are not covered by a harmonized standard, according to the specifications included in European Technical Assessment documents which are issued on the basis of a European Assessment Document. The performance of the different products to the relevant technical specifications is expressed in the Declaration of Performance on which the CE marking is based, indicating the product's compliance with the EU legislation and, therefore, enabling its free marketing within the European Union (European Union 2011).

Seismic Risk in Europe

In Europe since 2009, a collaborative research project between eighteen universities and research institutes named Seismic Hazard Harmonization in Europe (SHARE) is underway, with the main objective of providing a community-based seismic hazard model for the Euro–Mediterranean region with update mechanisms. This project, as it is declared on the SHARE website, "aims to establish new standards in Probabilistic Seismic Hazard Assessment practice by a close cooperation of leading European geologists, seismologists and engineers" (Woessner et al 2015).

Looking at the data provided by the SHARE project regarding the seismic hazard in Europe (Woessner et al 2015), the highest hazard is concentrated along the North Anatolian Fault Zone with values of peak ground acceleration (PGA) up to 0.75 g, considering the results for a 10% exceedance probability in 50 yr. This fault area runs from the southwestern coast of Turkey to the northern coasts of Albania crossing the western coast of Greece and the Cephalonia fault zone, see Fig 1. Similar hazard values can be found in Iceland, in the central-southern part of Italy, along the Apennines, in Calabria and Sicily, and in northeastern Romania, declining eastward toward Moldavia and the Black Sea. Moderate hazard levels characterize most areas of the Mediterranean coast, with the sole exception of Northern Croatia and the Eastern Alps, from Trentino to Slovenia, the Upper Rhine Graben (Germany/France/Switzerland), the Rhone valley in the Valais (southern Switzerland), and the northern foothills of the Pyrenees (France/Spain), where the Western Pyrenees exhibit larger hazard than their eastern counterpart. Moderate to high hazard levels can be found also in the Lisbon area, south of Belgrade (Serbia), northeast of Budapest (Hungary), south of Brussels (Belgium), in the region of Clermont-Ferrand (southeastern France), and in the Swabian Alb (Germany/Switzerland).

Seismic Design in Europe

The design of buildings for earthquake resistance is covered by EC8 (CEN 2004), a seismic design code founded on a force-based procedure. The energy dissipation capacity of the structure is implicitly taken into account by dividing the seismic forces obtained from a linear static or modal analysis by the so-called "behavior factor," q, corresponding to the associated ductility class,

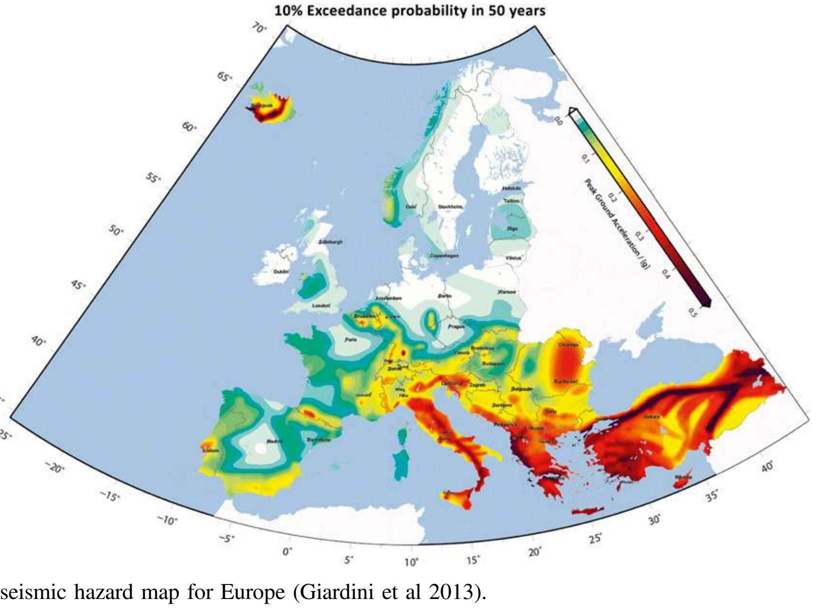

Figure 1. 2013 seismic hazard map for Europe (Giardini et al 2013).

which accounts for the nonlinear response of the structure associated with the material, the structural system, and the design procedures.

According to the general requirements, all structures shall be designed to withstand the design earthquake, ie the earthquake with a typical probability of exceedance of 10% in 50 yr for the "no collapse requirement" corresponding to the ultimate limit state and of 10% in 10 yr for the "damage limitation requirement" corresponding to the serviceability limit state, with an appropriate combination of resistance and energy dissipation. The capacity-based design philosophy is followed; ie a design method where some elements of the structure are chosen and suitably designed for energy dissipation, whereas others are provided with sufficient overstrength so as to ensure the chosen means of energy dissipation.

The provisions for the seismic design of timber buildings are currently included within Chapter 8 of EC8 "Specific rules for timber buildings." However, the current version of this chapter, which was released in 2004, is very short. Seismic design provisions are not given for most of the structural systems and materials currently used in the construction of timber buildings in Europe, thus forcing the structural designer to make assumptions in the seismic design, which not necessarily could be conservative. This is the reason why in 2014, the revisions of this chapter started, together with the ongoing revisions of the other Eurocodes, with the aim to provide an updated version by 2021. The working draft of the new chapter includes a detailed description of the different structural systems, a revised proposal of the table providing the values of the behavior factor q for the different structural systems according to the relevant Ductility Class, some capacity design rules for each structural type, and the values of the overstrength factors to be adopted for the design of the brittle components (Follesa et al 2018).

Seismic Design of CLT Buildings in Europe

Despite the fact CLT was invented in Europe around 20 yr ago, currently, with the only exception of the product standard (EN 16351 2015), there are no specific design provisions for CLT buildings within the European standards, including EC8 (CEN 2004). Previous practice made reference to the specifications included in the European Technical Approvals of the single producers for the calculation of CLT panels and assuming in the seismic design a q-behavior factor equal to 2.0, prescribed for buildings erected with glued walls and diaphragms by EC8.

However, the revision of the chapter for the seismic design of timber buildings within EC8 is in progress and will include CLT (Follesa et al 2015; Follesa et al 2018), as is the revision of the EC5 where CLT will be included as a wood-based product. According to the new specifications in EC8, CLT buildings will be classified as dissipative structures with two different values of the behavior factor q for the ductility class medium (DCM) and ductility class high (DCH), respectively classes 2 and 3. General rules and capacity design rules will be provided both at the building level and at the connection level to avoid any possible global instability or soft-story mechanism at a global level and to prevent any possible brittle failure in the ductile structural elements at a local level. The general rules will include a general description of the structural system, of the main structural components (walls, floors, and roof), type of connections generally used for the CLT system, and some regularity provisions, also common to other structural systems. No limitations on the maximum number of storys will be given.

According to these rules, a distinction is made between CLT buildings made of single, monolithic wall elements (of course considering production and transportation limits) and CLT buildings made of "segmented walls," ie walls composed of more than one panel, where each panel has a width not smaller than 0.25 h, where h is the interstory height, and is connected to the other panel by means of vertical joints made with mechanical fasteners such as screws or nails.

Capacity design rules are specified for the two ductility classes DCM and DCH, both at the building level and at the connection level. Regarding the former ones, in DCM, the structural elements which should be designed with overstrength to ensure the development of cyclic yielding in the dissipative zones are 1) all CLT wall and floor panels, 2) connections between adjacent floor panels, 3) connections between floors and underneath walls, and 4) connections between perpendicular walls, particularly at the building corners. According to the same requirements, the connections devoted to the dissipative behavior are 1) the shear connections between walls and the floor underneath, and between walls and the foundation and 2) anchoring connections against uplifts placed at wall ends and at wall openings. In DCH, the rules are the same as for DCM with the sole exception that also 3) the vertical screwed or nailed step joints between adjacent parallel wall panels within the segmented shear walls shall be regarded as dissipative connections (Follesa et al 2015).

The provisions for capacity design at the connection level are intended to provide a ductile failure mode characterized by the yielding of fasteners (nails or screws) in steel-to-timber or timber-to-timber connections and avoid any brittle failure mechanisms such as tensile and pull-through failure of anchor bolts or screws and steel plate tensile and shear failure in the weaker section of hold-down and angle brackets connections. A value of 1.3 is proposed for the overstrength factor of CLT buildings to be used in capacity-based design. Three alternatives are possible for the ductility classification of the dissipative zones: 1) providing minimum values of the required ductility ratio in quasi-static fully reversed cyclic tests, assuming failure has occurred when a 20% reduction of the resistance from the first to the third cycle backbone curve (CEN 2001) has taken place (values of 3.0 and 4.0 for the ductility ratio of shear walls, hold-downs, angle brackets, and screws, respectively, for DCM and DCH), 2) following prescriptive provisions on the diameter of fasteners and connected member thicknesses, or 3) ensuring the attainment of a ductile failure mode characterized by one or two plastic hinge formation in the metal fastener according to the European Yield Model (EYM) (Johansen 1949; Meyer 1957; CEN 2008).

DESIGN PROVISIONS IN CANADA

Regulatory Framework in Canada

The structural design of buildings in Canada is regulated by the NRC, enacting a set of specific and uniform regulations for construction in the NBCC. In 2005, an objective-based NBCC was introduced where each performance requirement is tied to a specific objective related to safety, health, accessibility, and efficiency. Before 2005, the building code consisted of certain rules named "prescriptive or acceptable solutions." After the implementation of the 2005 objective-based NBCC, another way for code compliance was made available through "alternative solutions." Any material, technology, or design which varies from acceptable solutions in Division B is considered as an alternative solution. These alternative solutions are performance-based design provisions and must achieve at least the minimum level of performance required in the areas defined by the objectives and function statements attributed to the applicable acceptable solution. In this concept, building performance of alternative solutions should exceed or at least equal the corresponding specification of the objectives and functional statements of an acceptable solution. The main purpose of adoption of objective-based code was to remove barriers to innovation.

The NBCC is the model building code which gets adopted and sometimes adapted by the individual Canadian provinces. For example, the government of British Columbia adopts the NBCC through an act that gives the power to establish regulations for the British Columbia Building Code to the provincial government. Provincial building codes can also go beyond the specification of NBCC. As an example, in 2009, British Columbia became the first province to allow the construction of six-story wood frame buildings with a specific area limit (BCBC 2012). The NBCC refers to the material standards for specific design aspects at the material, joint, component, and system levels. With respect to wood structures, Canadian Standards

Association (CSA-O86) "Engineering Design in Wood" is the relevant Canadian design standard (CSA O86 2014). CSA-O86 in turn refers to specific product standards such as the standard for CLT fabrication PRG 320 (ANSI/APA 2017).

Seismic Risk in Canada

The seismic design values for Canada are provided in the NBCC (NRC 2015) using the current seismic hazard model (mean ground motion at the 2% in 50-yr probability level). The current generation of seismic hazard models developed by the Geological Survey of Canada (GSC) elevated its qualitative predecessors to a fully probabilistic model (Adams et al 2015). Canada's west coast (ie the British Columbia coast) is situated in one of the world's most active seismic regions, known as the "Pacific Ring of Fire," and is the most earthquake-prone and earthquake-active area in Canada because of the presence of active an subduction zone in the basin of the Pacific Ocean (red zone in Fig 2). This is one of the few areas in the world where all three types of tectonic plate movement occur, and the GSC records more than 4000 earthquakes every year (NRCAN 2016).

Geological evidence indicates that the Cascadia subduction zone (which stretches from northern Vancouver Island to northern California) is capable of generating magnitude nine earthquakes every 300-500 yr. With geological data indicating that the massive M 9.0 'megathrust' earthquake off Vancouver Island on January 26, 1700 (Cassidy et al 2010), was the last major earthquake in this region, it is probable that another major earthquake will strike this region in the near future. Other than along the West Coast, other earthquake activity was also recorded in Yukon and the Northwest Territory, along the Arctic margins, and in the province of Quebec.

Seismic Design in Canada

For most projects, current seismic design in Canada is carried out in accordance with the Equivalent

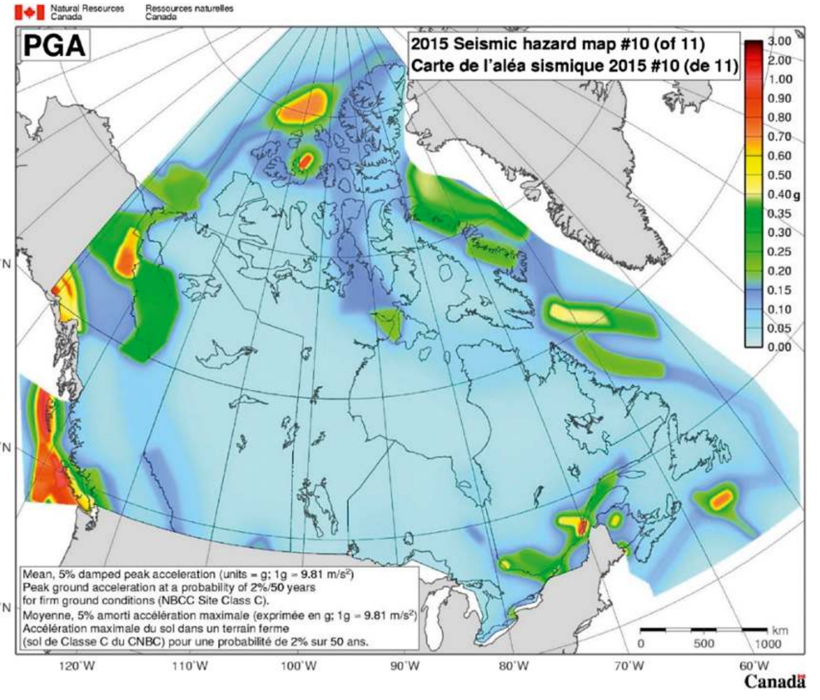

Figure 2. 2015 seismic risk map for Canada (http://www.earthquakescanada.nrcan.gc.ca).

Static Force Procedure where elastic forces are based on an initial elastic estimate of the building period combined with a design spectral acceleration for that period. Design force levels are reduced from the elastic level by applying code-specified force reduction factors. In NBCC, this reduction factor is the product $R_d \times R_o$ where R_d is the reduction factor for ductility and R_o is an overstrength factor. R_d reflects the reduction in force seen in a structure responding inelastically compared with the equivalent elastic structure and is a function of the system ability to deform beyond yielding. R_o represents the system reserve strength which comes from factors such as member oversizing in design and strain hardening in the materials. The values for these two R factors for different types of seismic force resisting systems (SFRS) are presented in the NBCC. Higher mode effects are also taken into account by multiplying the design base shear with a period-based factor as specified in the NBCC (NRC 2015).

Seismic Design of CLT Buildings in Canada

In 2014, a preliminary statement was introduced into to CSA-O86 that introduced CLT: "Clause 8 has been reserved for design provisions which will cover CLT manufactured in accordance with ANSI/APA PRG 320 standard" (CSA O86 2014). In 2016, a supplement to CSA-O86 was published which included detailed design provisions for CLT elements and connections in CLT (CSA O86 2016). Furthermore, Clause 11.9 "Design of CLT shear walls and diaphragms" was added providing guidance for the design of lateral load resisting systems composed of CLT.

The design provisions provided by CSA-O86 (CSA O86 2016) apply only to platform-type construction not exceeding 30 m in height. For high seismic zones, the building height is further limited to 20 m. Within these limitations, and meeting the connection and aspect ratio requirements as discussed in the following paragraph, and as long as wall panels act in rocking or in combination of rocking and sliding, it is stated that "seismic reduction factors of $R_d \leq 2.0$ and $R_o = 1.5$ shall apply to platform-type CLT structures." Any other CLT lateral load resisting system has to be treated as an alternative system and needs to be designed in accordance with the NBCC alternative solutions approach. For such systems, CSA-O86 states that "The seismic design force need not exceed the force determined using $R_d\ R_o = 1.3$.

The CSA-O86 (CSA O86 2016) provisions are based on the assumption that each CLT panel acts as rigid body and that the lateral resistance of CLT shear walls (and diaphragms) is governed by the connection resistance between the shear walls and the foundations or floors, and the connections between the individual panels. Energy-dissipative connections of CLT structures need to be designed such that 1) a yielding mode governs the connection resistance, 2) the connection needs to be at least moderately ductile in the directions of the CLT panel's assumed rigid body motions, and 3) the connection needs to have sufficient deformation capacity to allow for the CLT panels to develop their assumed deformation behavior. According to the underlying capacity-based design principle, all nondissipative connections are expected to remain elastic under the force and displacement demands that are induced in them when the energy-dissipative connections reach the 95th percentile of their ultimate resistance or target displacement. The expectation is that manufacturers of connection systems will make such data available to designers.

To prevent sliding from being the governing kinematic motion, the wall segments' height-to-length aspect ratio has to be within the limits of 1:1 and 4:1. Wall segments with a smaller aspect ratio need to be divided into subsegments and joined with energy-dissipative connections or, as stated before, the system needs to be designed according to the alternative solution procedure. Where the factored dead loads are not sufficient to prevent overturning, hold-down connections shall be designed to resist the factored uplift forces and transfer the forces through a continuous load path to the foundation. If continuous steel rods are used, they shall be designed to remain elastic at all times and shall not restrict the motion in the direction of the assumed rigid body. If connections of the CLT shear wall panels to the foundation or the floors underneath are designed to resist forces in both shear and uplift direction, the shear-uplift interaction shall be taken into account when determining the resistance of the CLT shear walls. Finally, CSA-O86 (CSA O86 2016) states that "deflections shall be determined using established methods of mechanics" without providing specific guidance on this issue other than that calculations shall account for the main sources of shear wall deformations, such as panel sliding, rocking, and deformation of supports, and that CLT panels may be assumed to act as rigid bodies.

DESIGN PROVISIONS IN THE UNITED STATES

Regulatory Framework in the United States

In the United States there are literally thousands of building codes when one considers modifications made at the local level. The federal government leaves building code adoption to the individual states and, in turn, states pass the responsibility to smaller jurisdictions such as counties, cities, and towns. The model building codes include the International Building Code, the International Residential Code, and the International Existing Buildings Code, and are the result of three past regional organizations agreeing to merge into one body known as the International Code Council (ICC). These building codes provide a general model for buildings in the United States and can be adopted at the State level in whole or in part, with amendments or modifications made at the local level. Larger jurisdictions, such as the city of Los Angeles, implement their own requirements resulting in their own building codes which represent the needs of their specific community and can be more stringent than the model codes.

For wood, the 2018 IBC (IBC 2018) references the National Design Specification for Wood (NDS 2018) and the Special Design Provisions for Wind and Seismic (SDPWS 2015). The IBC and many localized building codes refer to the American National Standards Institute (ANSI) consensus standards for different construction materials and, particularly, loading and design approaches. The most prominent and widely used consensus standard in the United States, which is not part of the ICC codes, is the American Society of Civil Engineers Standard 7 (ASCE 7-16 2016) which is a consensus-based standard that articulates natural hazard risk including seismic, applicable load combinations, and performance criteria such as drift limits.

Seismic Risk in the United States

Seismic risk in the United States is determined by the United States Geological Survey (USGS) which is part of the National Earthquake Hazards Reduction Program that was developed in 1977 through the Earthquake Hazard Reduction Act. The most recent maps have evolved to enable a uniform estimated collapse capacity (Luco et al 2007) formulation to take into account uncertainty in structural capacity across the United States. Figure 3 shows a seismic risk map, which is then used to develop a seismic response spectra to be used directly in design as explained in the next section. As one can see from Figure 3, the areas of high seismicity are the West Coast including areas more inland near Salt Lake City, Utah; the Central United States; Alaska; part of Hawaii; and near Charleston, SC. There are a large number of faults throughout the western portion of the United States with perhaps the most famous being the San Andreas fault in Southern California. Seismicity in the Central and Eastern United States is primarily a result of several large earthquakes that occurred hundreds of years ago.

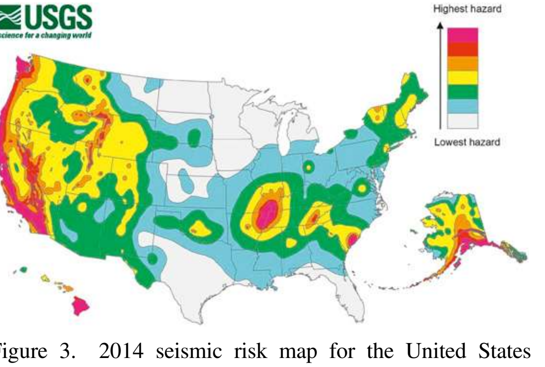

Figure 3. 2014 seismic risk map for the United States (www.USGS.gov).

Because there is less first-hand experience with earthquakes like in the Western United States, those jurisdictions are less motivated to adopt mitigation policies.

Seismic Design in the United States

Seismic design in the United States is performed using one of several methods, among them is the force-based ELFP outlined in ASCE 7 (ASCE 7-16 2016). However, it is also important to note that there are still areas in the United States which follow no building code and design is dependent on the contractor or developer, but in general, seismic regions of the United States are not among these parts of the country. The ELFP uses static equivalent loads placed horizontally at each floor diaphragm of the building and roof in such a way that it attempts to force a first-mode deformation/response. The loads are calculated based on a site-specific response spectrum that is developed from USGS maps, the period of the building, and the type of SFRS, eg steel special moment frame or wood shear walls. Three seismic performance factors are needed to develop the design seismic response spectrum and perform the seismic design with the ELFP, namely the response modification factor, R; the overstrength factor, Ω_o; and the displacement amplification factor, C_d. The R factor is used to reduce demand in designated yielding components or members within the SFRS, and a table is contained in ASCE 7 with these values agreed on by consensus. Other components within the SFRS can be applied with an overstrength factor to ensure they do not adversely affect the main component of the SFRS, and the displacement amplification factor estimates the inelastic drift of the SFRS.

The second seismic design approach outlined in ASCE 7 (ASCE 7-16 2016) is the alternate means approach which requires the engineering team to document details of their seismic design and achieve approval from the local building official at the discretion of the official. Often, a peer review of one or more subject matter experts is sought resulting in a time consuming and expensive process for the designers and the owner. However, this approach allows the development of new and innovative systems and can result in better efficiency in some cases.

Seismic Design of CLT Buildings in the United States

In the United States, ANSI/APA PRG320, the North American Standard for Performance-Rated CLT (ANSI/APA 2017), paved the way for the development of a chapter dedicated to CLT in the 2015 edition of the National Design Specification for Wood Construction® and recognition of CLT in the 2015 International Building Code. However, CLT SFRS are not yet recognized in current US design codes because there are no consensus-based seismic performance factors in ASCE 7. This means that CLT shear walls cannot be designed via the ELFPs, and the use of CLT for seismic force resistance can only be accomplished through alternative methods. As mentioned previously, this is a costly and time consuming process reducing the competitiveness of CLT to other materials such as steel and concrete.

A study is nearing completion to investigate the seismic behavior of CLT based shear wall systems and determine seismic performance factors for the ELFP (Amini et al 2016). That study follows the FEMA P-695 (FEMA 2009) methodology which is a systematic approach that integrates design method, experimental results, nonlinear static and dynamic analyses, and incorporates uncertainties. One key aspect of that study is the use of generic connectors which will eventually allow manufacturers to use one or more approaches to show equivalency and apply their connector in CLT design using the ELFP.

DESIGN PROVISIONS IN JAPAN

Regulatory Framework in Japan

The structural design of buildings in Japan is regulated by the BSL enforced by the Ministry of Land, Infrastructure, Transport, and Tourism (BSL 2016) with the objective to establish minimum standards regarding the structure, facilities, and use of buildings to protect life, health, and property, and thereby to contribute to promoting public welfare. Technical standards for all buildings to ensure building safety with regards to structural strength, fire prevention devices, sanitation, etc. are prescribed in the building code (BSL 2016). Structural specification and calculation methods are also prescribed in ministerial ordinances as the enforcement order and regulations of the BSL. Technical standards to be observed are established for each classification such as timber construction, steel construction, or reinforced concrete construction. Moreover, the safety of buildings for which the size exceeds a fixed limit must be ensured through structural calculations (BSL Article 20 2015). A performance-based code has been replacing the previously descriptive codes since 2000, allowing for use various materials, equipment, and structural methods, including timber-based construction, as long as the building satisfies specified performance criteria. BSL Article 37 (BSL Article 37 2015) of the designated building material also accounts for new structural members but testing methods and performance evaluation procedures must be prescribed for applicable structural members in advance. Regulation of fireproofing properties is indispensable for timber construction. The use of timber-based materials is not explicitly prohibited but for buildings with four storys or higher; therefore, noncombustible materials are required for vertical load resisting members.

Seismic Risk in Japan

Japan is located on the boundaries of four tectonic plates; consequently, severe earthquakes occur frequently. One year after the 1923 Great Kanto earthquake that destroyed approx. 450,000 buildings and causing 143,000 deaths in Tokyo and the surrounding regions, the Japanese Building Code required structural calculation for seismic force, effectively implementing the first seismic design requirements in the world. The 1995 Kobe earthquake destroyed 104,906 buildings and more than 6000 people lost their lives (FDMA 2006). As the results of severe damage of timber structures in the Kobe earthquake, simple calculation methods for shear wall design were defined. In 2011, the most powerful earthquake ever recorded in Japan struck in the Tohoku region and triggered a tsunami that cause nearly 16,000 deaths and destroyed 127,290 buildings (FDMA 2016).

The National Seismic Hazard Maps for Japan are prepared by the Headquarters for Earthquake Research Promotion (HERP 2017) and consist of two types of maps different in nature: the Probabilistic Seismic Hazard Maps, as shown in Figure 4, that combine long-term probabilistic evaluations of earthquake occurrence and strong motion evaluation, and the Seismic Hazard Maps for Specified Seismic Source Faults, which are based on strong motion evaluations for scenarios assumed for specific earthquakes. Besides these maps, the Architectural Institute of Japan publishes local maximum acceleration maps for the structural design of important buildings such as high-rise buildings whose height exceeds 60 m and nuclear plants.

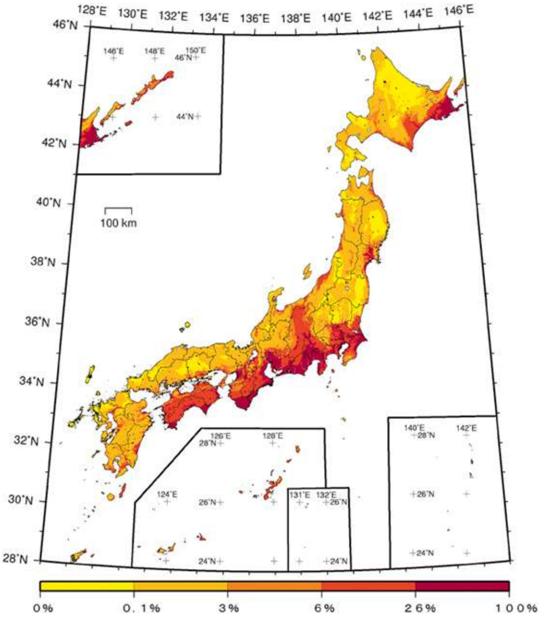

Figure 4. 2014 seismic risk map for Japan (www.jishin.go.jp/main/index-e.html).

Seismic Design in Japan

The BSL provides a Seismic coefficient map for structural design. The base shear for building design can be obtained from it and can then be reduced by the ductility of a building. The Japanese seismic design provisions were revised after severe damage was observed during the earthquakes in 1981 and again in 2000 when performance-based seismic methodologies and requirements were included. Both allowable stress design and ultimate limit state design, regarded as performance based seismic design, are defined as a minimum required procedure for buildings depending on the total floor area and height. For buildings built with structural specification, the strength of the main structural members is required in the enforcement order. Structural specifications are required for allowable stress design and ultimate lateral capacity design, but they are not required in limit strength calculation and time-history analysis. For small-scale buildings such as timber construction whose height and total area do not exceed 13 m and 500 m^2, respectively, only structural specifications and simple calculations are required. Buildings whose height exceed 60 m require a special permission from the minister and have to provide time-history response analysis to verify the seismic safety. The advanced time-history response analysis, however, can also be applied to all buildings.

Seismic Design of CLT Buildings in Japan

Before 2016, the standard strength for CLT was not included in the BSL, and time-history response analysis had to be applied as a seismic design procedure for CLT construction. CLT panels could already be used in buildings that do not require structural calculations or as nonstructural wall in all other buildings. To install structural CLT walls in conventional post and beam construction, a special permission from the ministry is required for only shear wall, and the wall capacity must be less than 9.8 kN/m. However, CLT walls are often too strong. CLT shear walls connected to post and beam structures with weak connections was one usage of CLT panels. Allowable stress design and ultimate lateral capacity design could not be applied because of no definition of structural specifications and standard strength for CLT panel, and limit strength calculation could not be applied because of no definition of standard strength as mentioned previously.

Government notifications on the structural design of CLT buildings (regulating applicable structural materials, required structural performance of connections, and methods of structural calculation for design) and the standard strength of CLT were issued in 2016. Subsequently, a guidebook (HOWTEC 2016a) and a manual on design and construction of CLT buildings (HOWTEC 2016b) were published in June and October 2016, respectively. The manual describes the standard specifications, eg defining the shear capacity of CLT walls for the simple allowable stress design as 10 kN/m for specific grades, lamina thicknesses, and connections. The capacity considerations account for the influence of ductility and connections between CLT panels and panels to other members. The required story shear performance is calculated from the seismic demand and compared with the sum of shear capacities of CLT walls in the simple method. In the ultimate limit state method, the story shear capacity is calculated from the pushover analysis. The design seismic load is calculated from the consideration of the ductility of the story defined as between 0.4 and 0.55 in the GN (HOWTEC 2016b) or obtained from pushover analysis.

DESIGN PROVISIONS IN NEW ZEALAND

Regulatory Framework in New Zealand

All structures in New Zealand need to comply with the New Zealand Building Code (NZBC 2004), which is a performance based code. The code requires a low probability of failure of the structure under gravity and lateral loads such as earthquakes. To obtain a building consent, a structure can be designed by adopting one of the three following pathways: acceptable solution, verification method, and alternative solution. As an example for an acceptable solution, the standard for timber-framed buildings NZS 3604 (NZS 2011) provides prescriptive rules for the design of light timber framing two-story residential structures in the form of standard section sizes and details. Structures outside of the scope of NZS 3604 can be designed following a verification method, based on engineering principles and the respective New Zealand loadings and material standards. Designs which adopt nonverification method design procedures, use new structural systems, or are made of materials which do not have a manufacturing or material design standard, can obtain a building consent through an alternative solution. In most cases, the authority having jurisdiction will require an independent peer review of the design by a competent engineer. Seismic actions are defined by the NZS for Structural Design Actions, Part 5: Earthquake Actions NZS 1170.5 (NZS 2004). It provides site-specific hazard spectra and defines the allowable analysis methods based on structural characteristics. The standard provides general design principles and drift limits under seismic actions, and refers to the material standards for the specific design and detailing of the structures.

The current New Zealand Timber Structures Standard NZS 3603 (NZS1993), which regulates the design of sawn timber, glulam members, plywood, and timber poles, was released in 1993, with four, mostly minor, amendments being released in subsequent years. Seismic considerations for timber structures are very limited and refer to general principles. It requires the use of the capacity design philosophy for limited ductile ($1.25 < \mu \leq 3$) and ductile ($3 < \mu \leq 4$) structures. Because the standard does not mention CLT, these structures need to be designed as an alternative solution. The New Zealand timber design standard AS NZS 1720.1 is currently under revision (DR AS NZS 2018) and will be released in early 2018. Although the new draft has a dedicated chapter for the seismic design of timber structures, it does not consider CLT as a structural material. This is because of the fact that CLT is relatively new to New Zealand, having currently only one local supplier and relatively little import from overseas.

Seismic Risk in New Zealand

New Zealand is a very active seismic area, having at least 11 major fault lines and a large number of smaller faults (see Fig 5). Many of the large faults

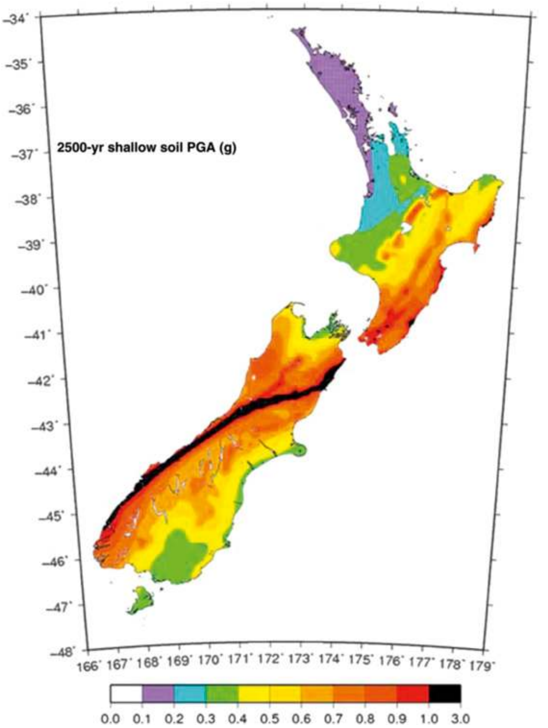

Figure 5. New Zealand National Seismic Hazard Model: Peak ground acceleration (units of g) with a 2% probability of exceedance in 50 yr on Class C (shallow soil sites) (Stirling et al 2012).

are oblique strike slip faults, with both sideways and vertical movement. The two most notorious faults are the Wellington Fault in the North Island and the Alpine Fault along most of the South Island. Whereas the former crosses New Zealand's capital city and corresponds to the collision zone of two of the Earth's great tectonic plates, the latter moves about 30 m per 1000 yr and has generated at least four magnitude 8 earthquakes in the past 900 yr (GNS Science 2018). Currently, PGA of up to 0.8 g for a 10% probability of exceedance in 50 yr is predicted along the Alpine Fault.

Aside from the large number of fault lines, the relatively large slip measured in some faults, the presence of subduction zones, alluvial deposits and reclaimed land creating basin effects, and near-fault effects make seismic actions often the governing design case for New Zealand structures. New Zealand has been mapped to account for the different seismic hazard levels, defined through the hazard factor Z. In addition, a near-fault factor N needs to be taken into account for structures close to a known fault line. The relatively low population density somewhat mitigates the seismic hazard exposure in New Zealand, but recent earthquakes such as the Canterbury Earthquake sequence in 2010 and 2011 and the Kaikoura Earthquake in 2016 have led to code changes and increased hazard factors in certain areas.

Seismic Design in New Zealand

Most buildings in New Zealand are designed according to the ELFP approach. This method is allowed for structures with a height of less than 10 stories, when the building period is less than 0.4 s, or when the structure is not classified as irregular and has a period smaller than 2 s. If the above mentioned criteria are not satisfied, or a three-dimensional model is required, a modal response spectrum analysis is normally used. The use of time-history analysis is not uncommon for complex structures. A number of structures are also designed based on the displacement-based design philosophy (Priestley et al 2007), especially for the case of innovative structural systems (base isolation, rocking structures, etc.). The use of DBD generally leads to a better understanding and control of the structural behavior under seismic loads. Currently this method is only codified for concrete rocking structures in the New Zealand concrete structures standards NZS3101 (NZS 2006).

The elastic site spectra can be determined based on the geographical location of the structure, the required return period of the seismic event, and the soil type. New Zealand has been subdivided into areas with assigned hazard factors Z, representing the likely PGA of an earthquake. In situations near known fault lines, the near-fault factor N needs to be added to the equation. In function of the importance level of the structure a probable return period and respective return period factor R of the ultimate limit state earthquake is determined. Based on the soil characteristics the spectral shape factor is determined depending on the building period. To obtain the design spectrum, the elastic spectrum is reduced by the inelastic spectrum factor k_{μ} and the structural performance factor S_p. The former is based on the ductility and damping of the structure and is also a function of the building period derived from the like-displacement and like-energy assumptions. The latter is a performance factor and considers the probable higher strength of materials, damping from nonstructural elements, higher capacity from structural redundancy, nonstructural elements, etc. Different formulations are given for the inelastic spectrum factor k_{μ} when using either equivalent static analysis or a modal response spectrum analysis.

When using equivalent static analysis, the base shear is obtained by multiplying the horizontal design action coefficient from the design spectrum by the expected seismic mass. The equivalent static forces can then be determined by distributing the base shear proportional to the height and mass of each floor up the building. To allow for the possible presence of higher mode effects, 8% of the base shear is applied to the top story. Capacity design principles and strength hierarchies need to be considered when designing ductile structures. Some allowance is made for higher mode effects in the equivalent static method, but special studies might be required for tall and flexible structures. The loading standard also differentiates between flexible and rigid diaphragms and requires the specific consideration of diaphragm flexibility in the load distribution.

Seismic Design of CLT Buildings in New Zealand

The use of CLT in New Zealand as a structural material only commenced in 2012 with the opening of the first CLT manufacturing plant in Nelson. Initially, the panels were mainly used as floor and roofing panels; however, recently, a number of structures have been completed entirely with CLT (Iqbal 2015; Parker 2015). The last two years have seen an increased interest in massive timber structures, prompting the import of CLT panels from Europe. Because of the novelty of CLT and the respective fastening systems in New Zealand, no generally accepted design philosophy of CLT structures is available. Each design is based on the individual designer's engineering judgment, referencing international literature and often using imported fasteners. Most of the early CLT structures in New Zealand were designed either elastically or with limited ductility ($\mu = 1.25$). Because most of these structures were residential and had a large amount of walls, the higher seismic loads could easily be transferred and higher ductility values were not necessarily targeted.

The other reason for using low seismic reduction factors is that only limited information is available on the ductility of proprietary fasteners, missing overstrength values, and lack of definition of brittle failure modes of CLT panels. Furthermore, the current timber design standard only specifically mentions nails as ductile fasteners, providing no information on the yielding failure modes of other fasteners. The soon-to-be-released new timber code allows for the use of the EYM, and as long as fastener ductility can be guaranteed, higher building ductility can be used.

Only for the recent multistory CLT structures (Dunedin Student Accommodation in Dunedin and Arvida Parklane in Christchurch) higher ductility values of two and three, respectively, were targeted. This was only possible by controlling the local ductility in the hold-downs by using the EYM, avoiding brittle failure modes in the panels by rational design of the highly stressed areas and using overstrength factors, and by taking into consideration all other elastic deformation contributions when verifying the global ductility. Testing at the University of Canterbury will provide better understanding of the overstrength of dowel connection in CLT and brittle failure modes (Ottenhaus et al 2018). This information, together with the new timber design standard will allow engineers to design CLT structures with more confidence under seismic actions.

DESIGN PROVISIONS IN CHILE

Regulatory Framework in Chile

The structural design of buildings in Chile is regulated by the General Law of Urban Planning and Construction (DFL N°458) and the General Urban Planning and Construction Ordinance (OGUC) (DS N°47). The latter document includes a series of technical standards whose compliance must be verified by the structural calculation project reviewer. This set of standards is composed of those that specify the loads that must be considered in the design and the standards for each material (reinforced concrete, steel, and wood) that must be adhered to. The OGUC contains specific indications for the construction of wooden structures of no more than two stories, in which no structural calculation is required and includes a series of requirements related to the protection of buildings against fire. In addition, OGUC establishes that for cases where there are no Chilean technical standards applicable, the structural calculation must be carried out on the basis of foreign standards. Regarding the design of wood structures, the applicable Chilean standard (NCh1198 2007) does not contain any regulations for the design of structures in CLT; however, the use of wood in any construction system is permitted, provided that the structural design complies with the OGUC requirements.

Seismic Risk in Chile

Chile is one of the most seismic vulnerable countries in the world; on average, every ten years an earthquake of magnitude greater than eight occurs. The high level of seismicity was documented by the more than 4000 earthquakes of magnitude greater than five recorded between 1962 and 1995 (Madariaga 1998), and more than 8000 earthquakes of magnitude greater than three in 2017. In this context, the largest seismic event ever to be recorded occurred in southern Chile in 1960, with a magnitude greater than 9.5. The greatest seismic activity in Chile is due to the subduction of the Nazca plate under the South American plate with an estimated speed of convergence between these plates of 60-70 mm per year (Khazaradse and Klotz 2003). The seismic activity in the country, to the south of the Taitao peninsula, which is lower than that occurring in the central and northern zone of Chile, is produced by subduction of the Antarctic plate under the South American plate and by sliding of the type between the Scotia plate and the South American plate. Figure 6 shows the plate tectonics of western South America that affects the rupture zone of the great earthquakes that occurred between 1868 and 2010. The zoning for the seismic design of buildings is based on probabilistic models that take into account the seismic history of the country and these tectonics.

Seismic Design in Chile and Design of CLT Buildings in Chile

The seismic design of buildings in Chile must be carried out in accordance with the provisions of the Chilean Standard NCh433 (1996), which are based on the force design procedure. This standard establishes two approaches: 1) static analysis method that requires a linear elastic behavior model to be used to represent the building and 2) modal spectral analysis method based on an acceleration design spectrum. The structural capacity to dissipate energy is incorporated in these two approaches through the response modification factors R_0 and R, respectively, which are developed based on the Chilean experience on the seismic behavior of the different types of structures and materials. In the static analysis method, this factor is applied by dividing the seismic

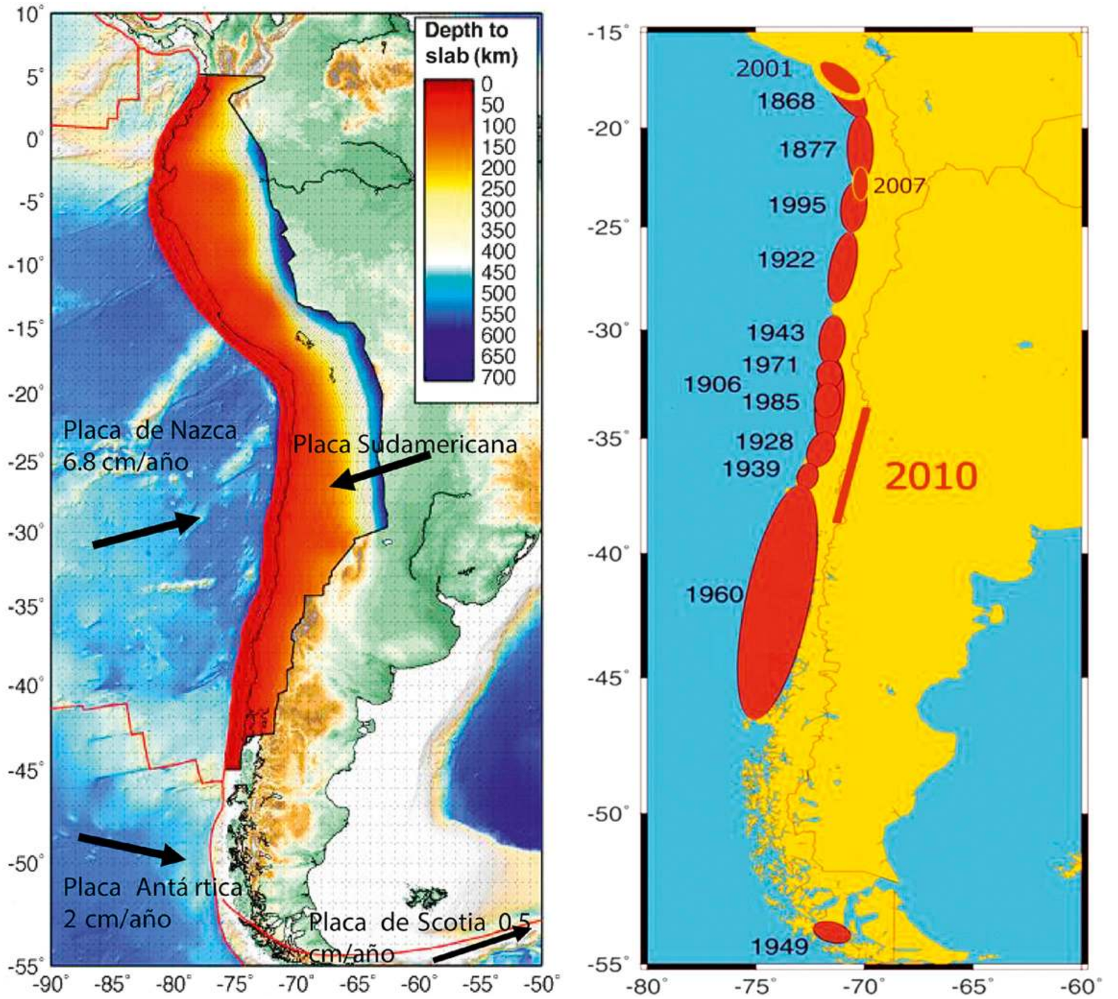

Figure 6. Tectonic plates of Western South America (www.csn.uchile.cl).

coefficient by the value that corresponds to the structural system and the building material. In the case of the modal spectral analysis method, the modification factor is contained in the denominator of the expression of the acceleration design.

The general provisions of NCh433 applied in conjunction with the specific material design standards are aimed at achieving structures that meet the following three conditions: 1) resist without damage seismic movements of moderate intensity; 2) limit damage to nonstructural elements during moderate intensity earthquakes; 3) avoid collapse during earthquakes of exceptionally severe intensity. The norm states that "Even though three levels of seismic intensity are mentioned, this norm does not define them explicitly." Regarding the seismic design of wooden buildings, NCh433 only contains values of response modification factor for light-frame and braced structures. As there are currently no specific regulations for the design of CLT buildings available in Chile, the provisions of NCh433 and the requirements specified in OGUC must be used for the seismic design of CLT buildings.

DESIGN PROVISIONS IN CHINA

Regulatory Framework in China

The Standardization Administration of the People's Republic of China defines the national standard management regulations and requirements and has the task to manage and produce technical specifications for products and systems for the construction sector. The Chinese Engineering Standards are divided into national standards, occupation standards, local standards, and enterprise standards. National standards shall be applied throughout the country, and other standards shall not conflict with national standards. For building design and construction, the Ministry of Housing and Urban-Rural Development of China enacted a set of specific and uniform regulations (labeled JGJ), whereas the Forestry Bureau is responsible for wood product standards and testing methods (labeled LY). Chinese Engineering Standards are divided into two categories of mandatory standards (labeled GB) and recommended standards (labeled T). For timber structures, applicable standards are the "Code for design of timber structures" (GB 50005 2017) and the "Technical Standard for Multi-story and High Rise Timber Buildings" (GB/T 51226 2017). These standards are updated every five or ten years based on scientific and technological advances. The Code for seismic design of building structures (GB 50011-2008) was revised and updated based on the Wenchuan Earthquake hazard survey and the latest seismic disaster mitigation technology.

Seismic Risk in China

China is located between the Circum-Pacific and the Eurasian seismic zones, which are two of the most active seismic zones in the world. According to historical earthquake records, Taiwan has the most earthquakes, followed by Xinjiang and Tibet, and coastal areas of China (Zhang et al 2009). According to the Seismic Fortification Intensity Zonation Map of China (2016), 7% of the total land area is considered at risk of magnitude eight earthquakes and 1% of the total land area is considered at risk of magnitude nine earthquakes (see Fig 7). Examples of large earthquakes are the magnitude 7.8 Tangshan Earthquake that in 1976 struck Tangshan, Hebei Province and surrounding regions, obliterated the city of Tangshan and killed more than 240,000 people, making it the deadliest earthquake of the twentieth century. In 2008, the Wenchuan 8.0 magnitude earthquake occurred in Sichuan province and caused the collapse of about 6.5 million buildings and the death of nearly 70,000 people (CEA 2018).

Seismic Design in China

Seismic design of buildings is performed to minimize damage and loss of lives and properties. In China, the design philosophy of "three-level and two-stage" is widely used in the Chinese national code, Code for Seismic Design of Building (GB 50011): Level 1) structures are subjected to frequently

Figure 7. 2016 seismic zoning map A of China (http://www.hundzj.gov.cn/).

occurring earthquakes (in a design period of fifty years, the exceedance probability is approximately 63.2% with a return period of 50 yr)—the structures either will be in service or only slightly damaged; Level 2) structures are subjected to the fortification earthquakes (in a design period of fifty years, the exceedance probability is approximately 10% with a return period of 475 yr)—the structure may be damaged but they should be serviceable with repair; and Level 3) structures are subjected to rarely occurring earthquakes (in a design period of fifty years, the exceedance probability is approximately 2-3% with a return period of 1642-2475 yr), they will neither collapse nor suffer damage that would threaten human lives. The "two stages" can be given as follows: Stage 1) The capacity and lateral drifts of a building structure should be examined under the basic load combination considering frequently occurring earthquakes by using the assumption of elastic performance of members and connections; and Stage 2) The elasto-plastic lateral drifts along the height of any building should be examined under rarely occurring earthquake conditions.

The method adopted in the Chinese Seismic Design Code determines the seismic forces acting on a structure using an indirect approach by transforming the earthquake-induced dynamic problem into a static problem under static load. Based on the acceleration responses due to ground motions, the inertia force of a structural system can be calculated and regarded as an equivalent load, which reflects the effects of the earthquake. The elastic acceleration spectrum is substituted by an earthquake influence coefficient, α, defined as the ratio of the horizontal seismic force acting on a single elastic system to that of gravity. The damping adjustment and parameter formations on the building seismic influence coefficient curve are provided by a graphical representation. For buildings with long periods, the decrease of α is considered in seismic influence coefficient curve.

Seismic Design of CLT Buildings in China

With the development and application of CLT worldwide, Chinese scholars started to do research on manufacturing processes, material properties of CLT, panel and connection structural performance, and seismic performance of CLT and mixed structures (He et al 2016; Xiong et al 2016a). A parametric study and time-history analysis of a tall CLT frame and concrete core mixed structural system showed that the vertical vibration and displacement compatibility of the hybrid structure are the special issues that should be considered. To substitute concrete and/or steel for wood in high density cities in China, an innovative super tall building with concrete frame-and-core structure inserted with CLT modular substructures was proposed and preliminarily designed (Xiong et al 2016b). The Chinese national standards GB 50005 (2017) and GB/T 51226 (2017) incorporated these findings and specify the requirements for CLT material properties, structural systems, and basic requirements of building height and design methodology of CLT structures.

CONCLUSIONS

In Europe, the current version of the structural Eurocode related to the seismic design of structures, EC8, is subjected to a comprehensive review, together with the other Eurocodes, and the new version will be released by 2021. Regarding the seismic design of CLT buildings, the new design rules will provide a significant improvement, including capacity-based design rules, detailing provisions and overstrength factors for dissipative zones which are currently totally missing for most of the structural types. Moreover the new standard will include a revision of the values of the behavior factors q and a clarification of the concept of static ductility and proposal of minimum values needed at the different scales (fastener, joint, and subassembly) to attain a certain value of the behavior factor and some guidance on the application of nonlinear static and dynamic analysis methods to timber structures. However, improvements are still needed especially regarding the seismic design and detailing of nonstructural elements; provisions for the use of displacement-based design, particularly for tall buildings; provisions for the seismic design of innovative low-damage structural systems; and recommendations for the estimation of the connection ductility in the dissipative regions.

In Canada, providing seismic design provisions into the wood design standard CSA-O86 (CSA O86 2016) presented a significant accomplishment. Nevertheless, there are several aspects where designers need further guidance. The standard refers to "methods of mechanics" and "engineering principles of equilibrium and displacement compatibility" but comes short of specific guidance. CSA-O86 does not provide design procedures for the resistance and deformation of LLRS composed of CLT and no specific guidance on how to facilitate the targeted kinematic mode a CLT wall will experience in the presence of vertical loads, especially for multi-panel walls, where the kinematic behavior may change during the loading as a function of the connection behavior. CSA-O86 does provide capacity-based design provisions that require the knowledge of 95th percentile connection strength values to ensure that they will remain elastic when the dissipative connectors have reached their ultimate resistance or target displacement, yet the standard does not provide the values for any connections. The designer need, therefore, to rely on test data obtained from the fastener manufacturer. As a cautionary note, it must be mentioned that NBCC is not yet referencing the current CSA-O86 standard and that further changes related to acceptable kinematic motions of CLT shear walls and the acceptable CLT panel aspect ratios might be introduced into the 2019 edition of CSA-O86.

In the United States, posttensioned rocking walls have received some attention with a recent study that examined the feasibility of designing up to 10 stories with this approach (Pei et al 2015). Supporting numerical models for that study were developed and a new study is underway that focuses on bidirectional assembly level testing, two-story shake table testing (Akbas et al 2017;

Ganey et al 2017), and will culminate by validating a resilience-based seismic design philosophy for tall wood buildings constructed of CLT with posttensioned CLT walls by testing a full-scale 10-story building on a shake table in 2020. The approaches developed within that project will serve as a guideline to approach building officials for midrise and tall wood building construction under the alternative methods provision in ASCE 7.

In New Zealand, the use of CLT is relatively new with only one local supplier available. Because CLT is not codified in New Zealand, only a small number of engineers are taking the lead on the seismic design of these structures, normally requiring a peer review to obtain building consent. Although the seismic risk in New Zealand is high to very high, most CLT structures are currently designed elastically or with only limited ductility targets. Higher ductility levels are often not required because of the limited size of the structures with only up to two storys and the large number of walls. The lack of guidance on the seismic design, missing overstrength factors, and limited knowledge on the brittle failure modes of CLT discourages the use of higher ductility levels. Although current research on the cyclic behavior of large force connections show promising results in terms of capacity and ductility, more information on overstrength and brittle failure modes is required to provide confidence in designing tall and large CLT structures. Higher ductility levels have been targeted through the use of innovative systems. An example of this is the Kaikoura District Council building (Iqbal 2015), which was designed using posttensioned, Pres-Lam walls and a displacement-based design approach. This building was subjected to the recent Kaikoura earthquake in 2016 with no signs of visible damage.

In Chile, to support the development of design guidelines for CLT structures, the government,

Table 1. Main differences in seismic design approaches and regulations.

Country/region	Status of CLT seismic design provisions	Applicable seismic force reduction factors	Scope of CLT seismic design standard provisions
Europe	Proposal in development for inclusion into EC8	$q = 2.0$ (DCM) $q = 3.0$ (DCM)	No height limitation, panel aspect ratio 1:5 to 4:1, and capacity protection using 1.3 overstrength factor
Canada	Regulated in CSA-O86 since 2016	$R_d\ R_o = 3.0$ (for structures within scope) $R_d\ R_o = 1.3$ (otherwise)	Height <30 m in low seismic regions; <20 m in high seismic regions; panel aspect ratio 1:1 to 4:1, and capacity protection using 95th strength percentile
United States	Proposal in development for inclusion into American Society of Civil Engineers Standard 7	$R = 3.0$-3.5 depending on the results of the FEMA P695 analysis and peer review	Height <20 m panel aspect ratio 2:1 to 4:1 and capacity protection using 1.15 for overturning restraint. Shear connectors not assumed to take any uplift
Japan	Notification 611, No.8	Ds = 0.4-0.55 ($=1/R$) depending on connectors, 0.75 for all structure	0.4-0.55: Connectors for bending moment are required with tensile ratio of 10%
New Zealand	CLT will not be included in 2018 current update	Connections with global ductility values of up to 3 are available	—
Chile	No CLT specific provisions in standard	$R = 2.0$ as default value for any structural system	—
China	Regulated in GB/T 51226 2017	Different approach to calculation of seismic forces without force reduction factors	Heights up to 56 m depending on seismic intensity and structural system, panel aspect ratio 1:2 to 3:1, and capacity protection using 1/0.85 overstrength factor

CLT, cross-laminated timber; DCM, ductility classes medium.

through the Development Corporation, has supported projects to determine the physical and mechanical properties of CLT using radiata pine, and to analyze the dynamic behavior of the CLT panel systems (González et al 2014; Pérez et al 2017) and develop a four-story building in CLT for social housing (Pina et al 2015). In China, the first actual CLT-steel hybrid structure "OTTO café" of China was built in Ningbo. The design was the work of the first prize of the First National Design Competition of Timber Structures for university students. With the policy support and development of materials and construction techniques, several multistory CLT buildings having been designed and will be built soon.

The previous discussion demonstrated that the increasing interest in and demand for CLT structures worldwide has produced a large body of research knowledge that is being integrated into design provisions. Many studies confirmed the good structural performance of CLT structures, including good seismic performance when using ductile connectors. As a consequence, CLT is increasingly gaining popularity in single and multistory residential and nonresidential applications worldwide, also in areas with high seismic activity. Designing and building CLT structures, also in earthquake-prone regions, is no longer a domain for early adopters, but is becoming a part of regular timber engineering practice. The increasing interest in CLT construction has resulted in multiple regions and countries adopting provisions for CLT into their engineering design standards. However, given the economic and legal differences between each region, some fundamental issues are treated differently, particularly with respect to seismic design. Table 1 summarizes the main differences in the seismic design approaches and regulations for the regions that were presented in this article.

REFERENCES

Adams J, Halchuk S, Allen T, Rogers GC (2015) Canada's 5th generation seismic hazard model, as prepared for the 2015 National Building Code of Canada in Proc. of the 11th Canadian Conference on Earthquake Engineering, July 21-24, 2015, Victoria, BC, Canada.

Akbas T, Sause R, Ricles J, Ganey R, Berman J, Lotus S, Dolan JD, Pei S, van de Lindt J, Blomgren H (2017) Analytical and experimental lateral load response of self-centering CLT walls. J Struct Eng 143(6):04017019.

Amini MO, van de Lindt JW, Rammer D, Pei S, Line P, Popovski M (2016) Determination of seismic performance factors for CLT building systems. WCTE 2016, Vienna, Austria.

ANSI/APA (2017) PRG 320, Standards for performance-rated cross-laminated timber. American National Standard, APA, Tacoma, WA.

ASCE (2016) Minimum design loads for building and other structures. ASCE Standard ASC/SEI 7-16, American Society of Civil Engineers, Reston, VA.

BCBC (2012) Building code of British Columbia, Office of housing and construction standards. National Research Council, Victoria, BC, Canada.

Brandner R, Flatscher G, Ringhofer A, Schickhofer G, Thiel A (2016) Cross laminated timber (CLT): Overview and development. Eur J Wood Wood Prod 74(3):331-351.

BSL Article 20 (2015) Guideline for building standard law, enforcement order and notification for structural design, p. 25, Article 20, Official Gazette Co-operation of Japan.

BSL Article 37 (2015) Guideline for building standard law, enforcement order and notification for structural design, p. 48, Article 37, Official Gazette Co-operation of Japan.

BSL (2016) Japan ministry of land, infrastructure, transport and tourism, building standard law. The Building Standard Law of Japan, Building Center of Japan, Tokyo, Japan.

Cassidy JF, et al. (2010) Canada's earthquakes: 'The good, the bad, and the ugly'. Geoscience Canada 37(1):1911-4850.

CEA (2018) China earthquake administration. http://www.cea.gov.cn/ (accessed November 2017).

Ceccotti A, Follesa M (2006) Seismic behaviour of multi-storey XLam buildings in Proc. COST Action E29, International Workshop—Earthquake Engineering on Timber Structures, pages 81-95, Coimbra, Portugal.

Ceccotti A, Sandhaas C, Okabe M, Yasumura M, Minowa C, Kawai N (2013) SOFIE project–3D shaking table test on a seven-storey full-scale cross-laminated timber building. Earthquake Eng Struct Dyn 42(13):2003-2021.

CEN (2001) EN 12512: 2001. Timber structures—Test methods—Cyclic testing of joints made with mechanical fasteners. European Committee for Standardization, Brussels, Belgium.

CEN (2004) Eurocode 8: Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings. European Committee for Standardization, Brussels, Belgium.

CEN (2008) EN 1995-1-1:2008. Eurocode 5: Design of timber structures—Part 1-1: General—Common rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.

Centro Sismológico Nacional (2018) Sismicidad y terremotos en Chile. Centro Sismológico Nacional/Universidad de Chile, Santiago, Chile.

CSA O86 (2014) Engineering design in wood. Canadian Standards Association, Ottawa, Canada.
CSA O86 (2016) Supplement. Engineering design in wood. Canadian Standards Association, Ottawa, Canada.
DFL N° 458 (1975) Ley General de Urbanismo y Construcciones.
Dimova S, Fuchs M, Pinto A, Sousa L, Nikolova B, Iannaccone S (2015) State of implementation of the Eurocodes in the European Union: Support to the implementation, harmonization and further development of the Eurocodes. Report 2015. EUR 27511. doi:10.2788/85493.
DR AS NZS (2018) Timber structures-Part 1: Design methods. Standards New Zealand, 1720.1, Wellington, New Zealand.
DS N°47 Ministerio de Vivienda y Urbanismo (2017) Normativa de Urbanismo y Construcciones.
EN 16351 (2015) Timber structures—Cross-laminated timber—Requirements. European Committee for Standardization, Brussels, Belgium.
European Union (2011) Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC, European Union, Brussels, Belgium.
European Union (2016) The European construction sector. A global partner. Internal market, industry, entrepreneurship and SMEs directorate general energy directorate general. Joint Research Centre (JRC). https://ec.europa.eu (accessed November 2017).
FDMA, Fire and Disaster Management Agency (2006) Hanshin-Awaji Great Earthquake. www.fdma.go.jp/bn/1995/detail/941.html (accessed November 2017).
FDMA, Fire and Disaster Management Agency (2016) Higashi Nihon Great Earthquake. www.fdma.go.jp/bn/higaihou.html (accessed November 2017).
FEMA (2009) Quantification of building seismic performance factors: FEMA P695. Federal Emergency Management Agency, Washington, D.C.
Follesa M, Fragiacomo M, Casagrande D, Canetti D, Tomasi R, Piazza M, Vassallo D, Rossi S (2018) The new provisions for the seismic design of timber buildings in Europe. Engineering Structures, Special issue.
Follesa M, Fragiacomo M, Vassallo D, Piazza M, Tomasi R, Rossi S, Casagrande D (2015) A proposal for a new background document of chapter 8 of Eurocode 8, paper 48-7-3 in Proc. 2nd International Network on Timber Engineering Research (INTER), Šibenik, Croatia.
Gagnon S, Pirvu C (2012) Cross-laminated timber (CLT) handbook. FPInnovations, Vancouver, Canada. 594 pp.
Ganey R, Berman J, Akbas T, Loftus S, Daniel Dolan J, Sause R, Blomgren HE (2017) Experimental investigation of self-centering cross-laminated timber walls. J Struct Eng 143(10):04017135.
Gavric I, Fragiacomo M, Ceccotti A (2015) Cyclic behavior of CLT wall systems: Experimental tests and analytical prediction models. J Struct Eng 141(11):04015034.
GB 18306-2016 (2016) Seismic ground motion parameter zonation map of China. National Standard of the People's Republic of China, China Criterion Press, Beijing, China.
GB 50005 (2017) Code for design of timber structures. China Architecture and Building Press, Beijing, China.
GB 50011 (2001) Code for seismic design of buildings, National Standard of the People's Republic of China, China Building Industry Press, Beijing, China.
GB/T 51226 (2017) Multi-story and high rise timber buildings. China Architecture and Building Press, Beijing, China.
Giardini D, Woessner J, Danciu L, Cotton F, Crowley H, Grünthal G, Stucchi M (2013) Seismic Hazard Harmonization in Europe (SHARE): Online Data Resource. doi: 10.12686/SED-00000001-SHARE.
GNS Science (2018) Major faults in New Zealand. https://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/Major-Faults-in-New-Zealand (accessed November 2017).
González P, Saavedra E, Perez E, Burgos C, Piña F, Wagner M (2014) Sistema constructivo en madera contralaminada para edificios. Servicios Forestales y de Exposiciones S.A., Santiago, Chile.
He M, Duo T, Zheng L (2016) State-of-the-art of research advances on multi-story timber and timber-hybrid structures. J Build Struct 37(10):1-9.
HERP (2017) Japanese Headquarters for Earthquake Research Promotion Report National Seismic Hazar Maps for Japan. www.jishin.go.jp/main/index-e.html (accessed November 2017).
HOWTEC (2016a) Guideline for 2016 CLT relative notifications. Japan Housing and Wood Technology Center, Tokyo, Japan.
HOWTEC (2016b) Design and construction manual for CLT buildings. Japan Housing and Wood Technology Center.
Hummel J (2017) Displacement-based seismic design for multi-storey cross-laminated timber buildings. PhD thesis, Kassel University Press, Kassel, Germany. 224 pp.
International Building Code (IBC) (2018) International Code Council, Washington, D.C.
Iqbal A (2015) Cross-laminated timber for building structures. SR336. BRANZ Report.
Kawai N, Miyake T, Yasumura M, Isoda H, Koshihara M, Nakajima S, Araki Y, Nakagawa T, Sato M (2016) Full scale shake table tests on five story and three story CLT building structures in Proc. 14th World Conference on Timber Engineering, August 22-25, 2016, Vienna, Austria.
Khazaradse G, Klotz J (2003) Short and long-term effects of GPS measured crustal deformation rates along the south-central Andes. J Geophys Res 108(B6):1-15.
Johansen KW (1949) Theory of timber connections. Int Assoc Bridge Struct Eng 9:249-262.
Lauriola MP, Sandhaas C (2006) Quasi-static and pseudo-dynamic tests on XLAM walls and buildings in Proc. COST Action E29, International Workshop—Earthquake Engineering on Timber Structures, pages 119-133, Coimbra, Portugal.
Luco N, Ellingwood BR, Hamburger RO, Hooper JD, Kimball JK, Kircher CA (2007) Risk-targeted versus current seismic design maps for the conterminous United

States in Proc. Structural Engineers Association of California Convention, Sacramento, CA.

Madariaga R (1998) Sismicidad de Chile. Fis Tierra 10: 221-258.

Meyer A (1957) Die Tragfähigkeit von Nagelverbindungen bei statischer Belastung. Holz Roh Werkst 15(2):96-109.

Miyake T, Yasumura M, Kawai N, Isoda H, Koshihara M, Tsuchimoto T, Araki Y, Nakagawa T (2016) Structural possibility of CLT panel constructions in High seismic area in Proc. 14th World Conference on Timber Engineering, August 22-25, 2016, Vienna, Austria.

Moroder D, Smith T, Dunbar A, Pampanin S, Buchanan A (2018) Seismic testing of post-tensioned Pres-Lam core walls using cross laminated timber. Eng Struct 167: 639-654.

NCh1198 (2007) Madera—Construcciones en madera—Calculo. Instituto Nacional de Normalizacion INN-Chile, Santiago de Chile.

NCh433 (1996) Diseno sismico de edificios. Instituto Nacional De Normalizacion, INN-Chile, Santiago de Chile.

NDS (2018) National design specification for wood construction. American National Standards Institute/American Wood Council (ANSI/AWC), Leesburg, VA.

NRC (2015) National building code of Canada 2015, Canadian commission on building and fire codes. National Research Council, Ottawa, Canada.

NRCAN (2016) Geological survey of Canada earthquake search (On-line Bulletin). Natural Resources Canada. http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php.52 (accessed November 2017).

NZBC (2004) New Zealand building code. New Zealand Government, Wellington, New Zealand.

NZS (1993) 3603. Timber structures standard. Standard Association of New Zealand, Wellington, New Zealand.

NZS (2004) 1170.5. Structural design actions. Part 5: Earthquake actions—New Zealand. Standard Association of New Zealand, Wellington, New Zealand.

NZS (2006) 3101. Concrete structures standard Parts 1 & 2: The Design of concrete structures and commentary. Standard Association of New Zealand, Wellington, New Zealand.

NZS (2011) 3604. Timber framed buildings. Standard Association of New Zealand, Wellington, New Zealand.

Ottenhaus LM, Li M, Smith T, Quenneville P (2018) Overstrength of dowelled CLT connections under monotonic and cyclic loading. Bull Earthquake Eng 16(2): 753-773.

Parker J (2015) Timber takes on new forms. BRANZ, Build Magazine. Build 149.

Pei S, Lenon C, Kingsley G, Deng P (2017) Seismic design of cross-laminated timber platform buildings using a coupled shear wall concept. J Archit Eng 23(3):06017001.

Pei S, van de Lindt JW, Popovski M (2013) Approximate R-factor for cross-laminated timber walls in multistory buildings. J Archit Eng 19(4):245-255.

Pei S, van de Lindt JW, Popovski M, Berman JW, Dolan JD, Ricles JM, Sause R, Blomgren H-E, Rammer DR (2015) Cross laminated timber for seismic regions: Progress and challenges for research and implementation. J Struct Eng 142:E2514001.

Pérez E, González P, Saavedra E, Tapia S, Torelli S, Orellana S (2017) Mechanical characterization and hysteretic behaviour of CLT panels made of Chilean radiata pine in Proc. 16th World Conference on Earthquake Engineering, January 9-13, 2017, Santiago, Chile.

Pina F, González P, Burgos C, Saavedra E (2015) Seismic design of a mid-rise building in Chile using radiate pine cross laminated timber in Proc. 11th Canadian Conference on Earthquake Engineering, July 21-24, 2015, BC, Canada.

Popovski M, Gavric I (2015) Performance of a 2-story CLT house subjected to lateral loads. J Struct Eng 142(4): E4015006.

Popovski M, Schneider J, Schweinsteiger M (2010) Lateral load resistance of cross laminated wood panels. Pages 20-21, Curran Associates in Proc. 11th World Conference on Timber Engineering, June 20-24, 2010, Riva del Garda, Italy.

Priestley MJN, Calvi GM, Kowalsky MJ (2007) Displacement-based seismic design of structures. IUSS Press, Pavia, Italy. 721 pp.

SDPWS (2015) ANSI/AWC Special design provisions for wind and seismic. American Wood Council, Leesburg, VA.

Shahnewaz M, Tannert T, Alam MS, Popovski M (2017) In-plane stiffness of cross-laminated timber panels with openings. Struct Eng Int 27(2):217-223.

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Van Dissen R, Berryman K, Lamarche G (2012) National seismic hazard model for New Zealand: 2010 Update. Bull Seismol Soc Am 102(4):1514-1542.

van de Lindt JW, Amini MO, Rammer D, Pei S, Line P, Popovski M (2016) Progress in developing seismic performance factors for cross laminated timber in the United States via the FEMA P695 methodology in Proc. ASCE Structures Congress, April 3-5, Boston, MA.

Woessner J, Laurentiu D, Giardini D, Crowley H, Cotton F, Grünthal G, Hiemer S (2015) The 2013 European seismic hazard model: key components and results. Bull Earthquake Eng 13(12):3553-3596.

Xiong H, Ouyang L, Wu Y (2016a) State-of-the-art on research of tall wood buildings. J Tongji Univ 44(9): 1297-1306. (Natural Science).

Xiong H, Ouyang L, Wu Y (2016b) Preliminary design of a novel hybrid tall building with concrete frame-tube and light wood boxes in Proc. World Conference on Timber Engineering, August 22-25, 2016, Vienna, Austria.

Yasumura M, Kobayashi K, Okabe M, Miyake T, Matsumoto K (2015) Full-scale tests and numerical analysis of low-rise CLT structures under lateral loading. J Struct Eng 142(4): E4015007.

Zhang X, Yang G, Lu X, Li M, Yang Z (2009) Relation between the characteristics of strong earthquake activities in Chinese mainland and the Wenchuan earthquake. J Earth Sci 22:505-518.