Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Seismic Modelling and Analyses of Timber Structures

Zhiyong Chen[1*], Marjan Popovski[2], Chun Ni[3], and Dorian Tung[4]

[1] Scientist, Sustainable Construction, FPInnovations, Vancouver, Canada
[2] Lead Scientist, Sustainable Construction, FPInnovations, Vancouver, Canada
[3] Lead Scientist, Sustainable Construction, FPInnovations, Vancouver, Canada
[4] Manager, Sustainable Construction, FPInnovations, Vancouver, Canada
[*]zhiyong.chen@fpinnovations.ca (Corresponding Author)

ABSTRACT

Traditional timber structures provide satisfactory seismic performance due to such features as light weight, high strength-to-weight ratio, structural redundancy, elastic deformation capacity, and the ductility of connections. Nowadays, however, design trends aim for greater heights and longer spans, resulting in challenging seismic designs. Numerical modelling is essential in investigating the seismic response and demonstrating the performance-based design of structures. Timber structures subjected to seismic forces are usually characterised by highly non-linear behaviour, strength and stiffness degradation, and pinching effects on their hysteretic behaviour. These aspects may pose significant challenges for modelling of timber structures.

A global collaboration, including research institutes, consulting firms, manufactures, software companies, and government and associations, was initiated by FPInnovations in 2020 to develop a guide to support the application of numerical modelling for analysis and design of timber structures, and development and optimisation of wood-based products and systems. The developed "Modelling Guide for Timber Structures" (web.fpinnovations.ca/modelling) includes efficient modelling methodologies, analysis methods, and robust evaluation criteria for evaluation of the response of timber structures under seismic and wind loads, as well as their robustness in progressive collapse. It also includes development of basic principles for the application of computer modelling in timber building design, including modelling assumptions, validation of assumptions and modelling results, and demonstrating compliance with the building codes.

This paper provides a high-level overview of seismic modelling and analyses of timber structures covered in the modelling guide, including a comparison among timber, steel, and concrete structures, in terms of modelling emphases, key modelling principles, methods, and techniques specific for timber structures, as well as modelling approaches and considerations for timber-based load resisting systems and analysis approaches and considerations for timber structures during earthquake events. The information provided in this paper aims to assist practicing engineers in applying computer modelling to timber structures. It also enriches researchers' resources for advanced computer modelling of timber systems and assists software companies to identify the gaps and upgrade programs accordingly to accommodate advanced computer modelling of timber structures.

Keywords: Timber Structures, Numerical Modelling, Seismic Analysis, Seismic Response, Performance-based Design

INTRODUCTION

Currently, more than half of the world's population lives in densely populated urban areas, many of which are in high seismic regions. This exposes people to potentially damaging earthquakes. During an earthquake, the ground acceleration, velocity, and displacement (referred to as a ground motion) are transmitted through the structures and generate inertial forces and lateral (and vertical) displacements which a building must be able to sustain without collapse. For that reason, quantifying the seismic response of a building is one of the most important aspects of analysis and design of buildings in active seismic regions. Traditional timber structures provide satisfactory seismic performance due to such features as light weight, high strength-to-weight ratio, structural redundancy, elastic deformation capacity, and the ductility of connections [1]. Nowadays, however, design trends aim for greater heights and longer spans, resulting in challenging seismic designs. Numerical modelling is essential in investigating the seismic response and demonstrating the performance-based design of structures. Timber structures subjected to seismic forces are usually characterised by highly non-linear behaviour, strength and stiffness degradation, and pinching effects on their hysteretic behaviour. All these aspects may pose significant challenges for modelling of timber structures.

A global collaboration, including research institutes, consulting firms, manufactures, software companies, and government and associations, was initiated by FPInnovations in 2020 to develop a guide to support the application of numerical modelling for analysis and design of timber structures, and development and optimisation of wood-based products and systems. The developed "Modelling Guide for Timber Structures" [2] includes modelling methodologies, analysis methods, and robust evaluation criteria for evaluation of the response of timber structures under seismic and wind loads, as well as their robustness in progressive collapse. It also includes development of basic principles for the application of computer modelling in timber building design, including modelling assumptions, validation of assumptions and modelling results, and demonstrating compliance with the building codes. This paper provides a high-level overview of seismic modelling and analyses of timber structures covered in the modelling guide, including a comparison among timber, steel, and concrete structures, in terms of modelling emphases, key modelling principles, methods, and techniques specific for timber structures, as well as modelling approaches and considerations for timber-based load resisting systems and analysis approaches and considerations for timber structures during earthquake events. The information provided in this paper aims to assist practicing engineers in applying computer modelling to timber structures. It also enriches researchers' resources for advanced computer modelling of timber systems and assists software companies to identify the gaps and upgrade programs accordingly to accommodate advanced computer modelling of timber structures.

DIFFERENCE AMONG TIMBER, STEEL, AND CONCRETE STRUCTURES

Every structural material has unique mechanical characteristics. Consequently, different design strategies have been adopted for structural systems using different materials to optimise the material use. The structural behaviour and modelling emphases of structural systems with different materials vary accordingly.

Steel is a ductile material and is generally considered to be a homogeneous, isotropic, elastoplastic material with equal strength in tension and compression. Due to their high strength-to-weight ratio, steel elements are, in general, relatively slender. The design should account for the buckling resistance of slender compression and bending elements. Care is needed to ensure that connections do not unduly influence the overall response of a steel structure, especially for seismic design. To model steel elements and connections, material models must simulate the homogeneous, isotropic, and elastoplastic behaviour of steel.

Reinforced concrete (RC) is a composite material that uses concrete along with steel reinforcement bars, plates, or fibres so that concrete provides the compressive strength and steel provides the tensile strength primarily. As a composite material, maintaining composite action requires the transfer of load between the concrete and steel that is achieved by means of bond (anchorage). Thus, detailing of reinforcement, particularly for seismic conditions, is a key design aspect for RC structures. For simple or equivalent models, RC elements can be simulated using elastic material models with effective stiffness, while an inelastic mechanism can be simulated using plastic hinges. With respect to complex or detailed models, typically, the constitutive response of the concrete and reinforcement comprising the RC are modelled separately.

Wood has characteristic anisotropy due to its fibrous structure and can be considered as a material with three-dimensional orthotropy. Its stiffness and strength properties vary as a function of grain orientation among the longitudinal, radial, and tangential directions. The failure modes and the stress-strain relationships of wood depend on the direction of the load relative to the grain and on the type of load (tension, compression, or shear). For wood in tension and shear, the stress-strain relationship is typically linear, and the failure mode is brittle, while for wood in compression, the stress-strain relationship is typically nonlinear, and the failure mode is ductile. Because of their anisotropic mechanical properties, timber elements possess much higher stiffness and strength in the parallel-to-grain direction than in the perpendicular directions. Due to the presence of growth characteristics (e.g., knots), which significantly impair the tension and shear strength of wood, timber elements are most suitable for use in resisting compression parallel to the grain, followed by bending. Tension strength parallel-to-grain is as good or better than compression strength parallel-to-grain; however, the tension connections are prone to brittle failure. Tension perpendicular to the grain should be avoided or minimised in timber elements whenever possible because the capacity of wood in this direction is limited. The main area that requires attention in the design of timber structures is connections. Timber connections typically govern the strength of timber structures (either light wood-frame structures or mass timber structures) and can contribute significantly to the stiffness of the structures. Timber elements generally can be simulated using orthotropic elastic material models. In some cases, such as balloon-type mass timber walls, elastoplastic behaviour of timber elements must be included in the material models at the wall bottom that connects to the foundation. Compared to other connections, timber connections are much more complex due to the highly variable anisotropic mechanical properties of wood, existing growth characteristics such as splits and knots, and other effects, such as moisture content and temperature. Various types of failure modes can occur in timber connections, and they should have ductile failure modes, such as yielding, rather than brittle modes, such as splitting. When properly designed, timber connections can be simulated using models that represent the connection stiffness and strength. For analysing timber systems under cyclic loading, suitable hysteretic models are required to accurately reflect the structural response of timber connections and assemblies, as these may possess highly pinched hysteresis and degradation of strength and stiffness.

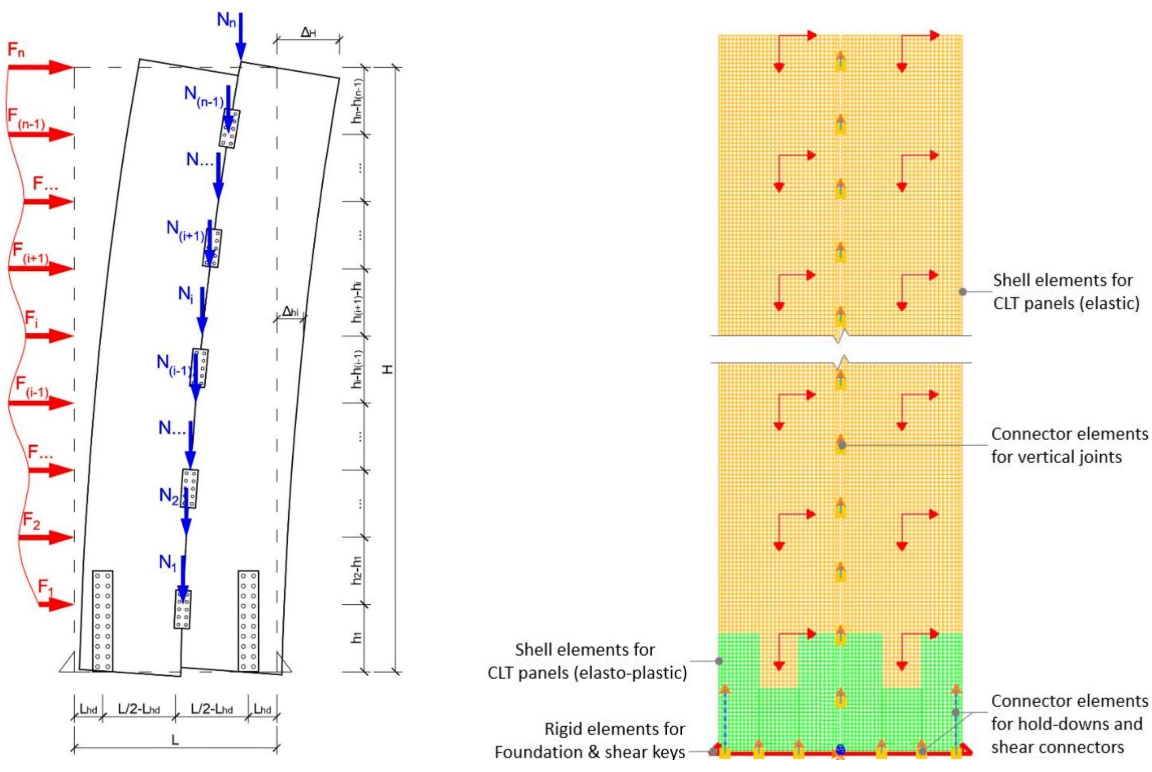
General comparisons, in terms of material and structural behaviour, and modelling emphases, among timber, steel, and RC are presented in Chapter 2 [3] of the modelling guide. Selected timber structural systems with analogous ones from steel and concrete are also compared.

MODELLING METHODS AND CONSIDERATIONS

Various numerical modelling methods are available for simulating the seismic response of structures under different loading conditions. This section briefly summarises four types of modelling approaches. More information can be found in Chapter 3 [4] of the modeling guide. This paper will focus on the FE modelling methods.

Mechanics-based modelling

Mechanics-based modelling, also called analytical modelling, is used to calculate the forces and deformation in a structure induced by various actions through applying engineering principles and fundamental mechanics. It usually involves establishing and solving equilibrium, compatibility, and constitutive equations. Hand calculation or any engineering calculation program can be adopted depending on the complexity of the equations. Mechanics-based models provide simple methods that help understand and predict the performance of structures. Such models are suitable for conceptual designs and for verifying the results obtained from complex finite element (FE) models. Figure 1(a) shows two mechanics-based models developed for balloon-type CLT walls by Chen and Popovski [5]. Once such models are developed, the analysis of corresponding structures with various key parameters (e.g., sensitivity analysis) is straightforward. These types of models are more suitable for analysing relatively simple problems (e.g., static performance) of uncomplicated structures (e.g., elastic material behaviour and/or boundary conditions). With respect to structures for which mechanics-based models do not exist or their development outweighs the benefit, FE modelling is a more efficient approach.



(a) (b)

Figure 1. Coupled balloon-type CLT shear wall: (a) mechanics-based model and (b)FE model.

Finite element modelling

In this modelling approach, the structural components and connections are developed using available FE software. The software develops and solves equilibrium equations, compatibility equations, and constitutive equations. Problems ranging from simple to complex (e.g., time-history analysis) and models with different levels of complexity (e.g., nonlinear material behaviour and boundary conditions) can be analysed by FE modelling, which is usually limited by software capacity (e.g., material models).

In terms of model scale, two types of models are available: microscale and macroscale. Microscale models form a broad class of computational models that simulate fine-scale details. In contrast, macroscale models amalgamate the details into selected coarse-scale categories. The goals and complexities of the models determine which modelling scale is used for a specific work. In the area of structural engineering, microscale models are commonly used in analyses of structural components and connections, with testing results of materials as model input. These models focus on how the behaviour of the modelled object is influenced by its geometric and material properties. In contrast, macroscale models are widely used in the analyses of structural assemblies and entire buildings. For structures where the storey shear deformation is the major component induced by lateral loads, such as low-rise light wood-frame buildings, mass-spring-damper (Macroscale) models can be used to simulate the entire building or the main lateral load-resisting assemblies at each storey. When bending deformation cannot be ignored under lateral loads (e.g., balloon-type mass timber shear wall structures), mass-spring-damper models are no longer suitable, and the lateral load-resisting assemblies must be modelled in a relatively more detailed approach. The connections in these assemblies, however, can be simulated using suitable nonlinear hysteretic springs. Figure 1(b) shows a FE model using macro-connection elements for a coupled balloon-type CLT shear walls [6].

In the FE modelling approach, the structural components and connections should be developed using any type of software. Because of the anisotropic material characteristics of wood, orthotropic material properties are required for the 2D or 3D model input for wood-based products. When the capacity design is used, the timber structural components that are capacity-protected can be modelled as orthotropic elastic members. Connections play a critical role in any timber structural model in terms of stiffness, ductility, and energy dissipation of the entire system. Connections that experience semirigid behaviour can be modelled using spring or connection elements. In cases of conducting nonlinear analyses (pushover or nonlinear dynamic analysis), suitable backbone curve models that can represent the yielding and post-yield behaviour of the connections, as well as hysteretic models that can represent the energy dissipation and the pinching effect of timber connections, must be used. As timber connections have high variability in stiffness and strength, the ranges of these parameters must be established during modelling, and the lower and upper bounds of the connection mechanical properties should be considered. Specific key connections should be considered as semirigid joints when calculating the deformation or stiffness and the natural period of vibration of the building. Upper bound limits should also be used when analysing the natural period of vibration of the buildings because simplified numerical models can easily produce unrealistically high and therefore nonconservative natural vibration periods.

Floor and roof diaphragms as horizontal assemblies distribute the gravity and lateral loads to load-resisting assemblies underneath. Diaphragm flexibility is a key factor affecting the lateral load distribution to the walls and other elements below. It is suggested that diaphragms be modelled in structural models according to their stiffness and deformability characteristics [7]. Nonstructural components, such as gypsum wallboard, provide considerable additional stiffness to the lateral load-resisting systems. Engineers must exercise judgment and follow code provisions, if present, on whether the contribution of nonstructural components should be considered in the model.

Hybrid simulation

Evaluation of the performance of structures has traditionally been explored using either experimental or modelling methods. Full-scale testing is generally viewed as the most realistic method for evaluation of structural components, assemblies, or even entire structures. The testing methods, however, require full-scale testing set-up (e.g., strong floor and strong wall testing facilities, or a shaking table) which are only available at some universities and institutes, and are mostly out of reach for most design practitioners. Furthermore, issues of size, equipment capacity, and availability of research funding continue to limit the use of full-scale testing of structures. Numerical modelling, on the other hand, is limited to solving specific types of problems and in many cases fails to capture complex behaviours or failure modes of structures or some components. Combining both experimental and modelling tools in a single simulation, while taking advantage of what each tool has to offer, is referred to as hybrid simulation [8-10]. Figure 2 schematically shows the hybrid simulation for a braced timber frame structure. In hybrid simulation of timber buildings, the entire structure is simulated and analysed by structural analysis software or a general-purpose FE software, while key structural components, connections, or assemblies are tested in a laboratory. At each time step of the displacement-based numerical integration of the equations of motion, the trial displacement calculated by the software is applied to the specimen. The force feedback of the specimen is then used by the software to check equilibrium prior to proceeding to the next time step. This way, the dynamic response of the entire building can be obtained with the real input from the tested components, connections, or assemblies. Hybrid simulation is suitable for complex timber buildings, particularly resilient buildings with structural fuses, because nonlinearity is typically concentrated at connections that are complex and can be tested in a laboratory without significant efforts. The remaining structure which is capacity designed and therefore considered to behave linearly, can be easily modelled with accuracy.

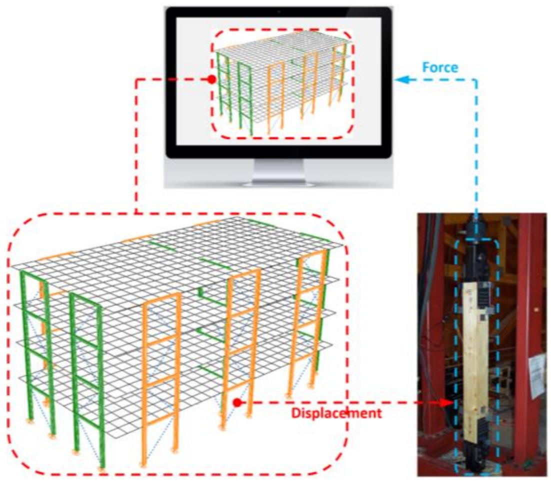


Figure 2. Schematic diagram of hybrid simulation for braced timber frames.

Material-based modelling

Over the past several decades, digital progress has transformed the entire construction industry, ushering in a technological era now known as the fourth industrial revolution. New digital technologies, including Building Information Modelling (BIM) and artificial intelligence (e.g., machine learning), began to enter the industry, gradually changing how infrastructure, residential and non-residential buildings are designed, constructed, operated, and maintained. More refined models, which are capable of exchanging construction details among different areas such as architecture, fabrication, and construction, and reducing or even eliminating the need for large-scale tests and calibrations, are desired for design and analysis of structural assemblies, or entire structures. Rapid development of high-performance computing (e.g., cloud computing), more comprehensive constitutive models for the material behaviour [11-13], and more accurate contact models provided a solid foundation for use of more refined structure models. In order to fulfill the new demand of the construction industry, a material-based modelling method was developed by Chen and Popovski [14] to simulate the seismic response of post-tensioned shear walls. The material-based models possess necessary details/parameters to support the design information exchange between BIM and structural modelling, while providing strategic simplifications to reduce the computation cost. Since sufficient details on the material and geometrical properties, and boundary conditions have been considered, the developed model can accurately predict the behaviour of the modelled structures with minimum verification (or even without calibration). Only the material (physical and mechanical) and geometrical properties of the components and connections are required as input for the material-based models. The material-based modelling method was adopted in the modelling of post-tensioned CLT walls shown in Figure 3. The seismic response, in terms of flag-shape hysteresis loops of the post-tensioned shear walls is automatically derived since the post-tensioned wall behaves in a multi-linear elastic way and the energy dissipators behave in an elastoplastic way. With this modelling method, the parametric structural design can be done more easily and the gap between the BIM and other areas of modelling can be bridged, while expanding the virtual design and construction.

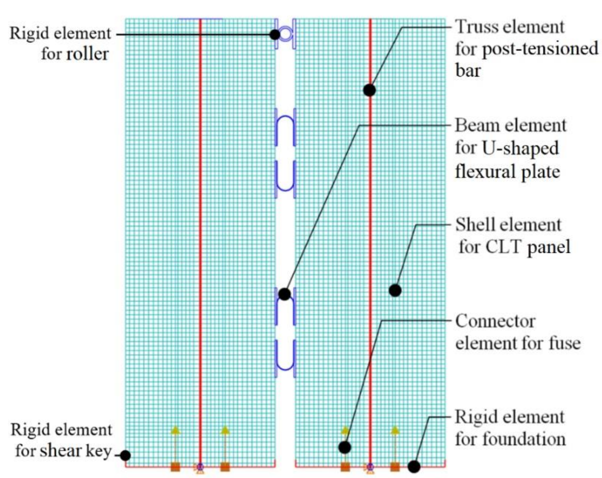


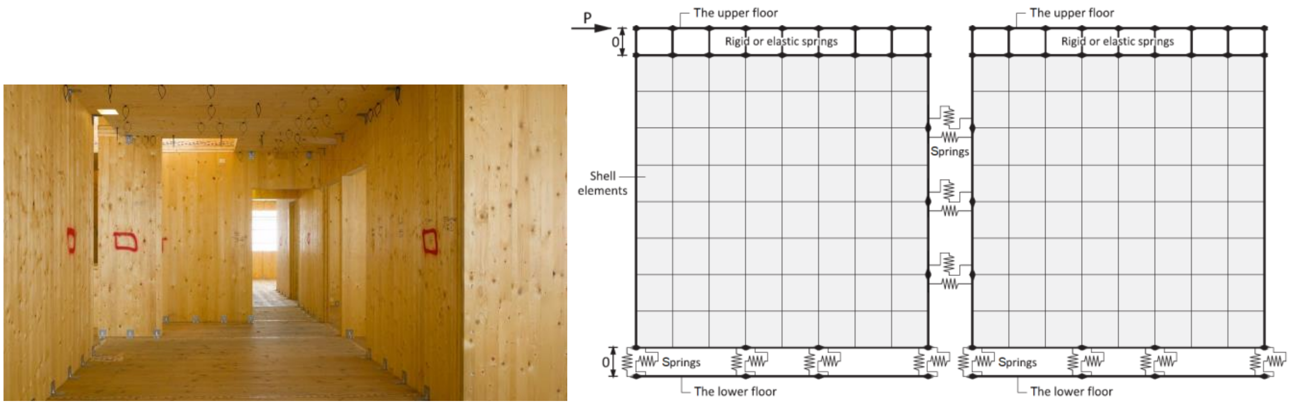
Figure 3. Material-based model for post-tensioned coupled CLT.

MODELLING OF MASS TIMBER STRUCTURES

Mass timber structures are a viable solution for taller and larger construction. The existing mass timber lateral load-resisting systems include platform-type shear walls, balloon-type shear walls, post-tensioned shear walls, braced frames, and moment frames. Below is a summary of the modelling approaches and considerations for such structural systems. More details can be found in Chapter 7.2 [6] of the modelling guide.

Platform-type shear walls

CLT structures are typically built using a platform-type approach where the floor at each storey is used as the base for erecting the CLT walls of the storey above. The height of the CLT walls is therefore equal to the storey height. At each storey, gravity loads are transferred through CLT floor panels. Because gravity loads are cumulative, the maximum building height is usually governed by the perpendicular-to-grain compression resistance of the CLT floor panels at the lowest storey. Otherwise, specific solutions are needed to efficiently transfer gravity loads between wall panels in adjacent storeys. Figure 4 (a) shows a typical storey of a multistorey CLT building. The CLT walls are connected to the CLT floors using metal brackets with fasteners (e.g., nails or screws).



(a) (b)

Figure 4. (a) Platform-type CLT building, Murray Grove (Courtesy of Waugh Thistleton Architects), and (b) FE models for coupled CLT shear walls.

Unlike RC shear walls, CLT panels are typically capacity-protected, and the connections govern the capacity of the CLT shear walls. With respect to finite element models for structural analysis, CLT panels can be simulated using shell elements, while shear connectors, hold-downs, and vertical joints can be simulated using spring elements, as illustrated in Figure 4 (b). The modelling input relies on many factors, such as modelling objectives and analysis types. Generally, orthotropic elastic properties [15] are assigned to CLT panels because they are capacity designed, while input on stiffness and strength is required for the connections. CLT material properties are provided in FPInnovations CLT Handbook [16] and are available in some design software programs, e.g., Dlubal and Altair. For nonlinear time-history analysis, a hysteretic model capable of stiffness and strength degradation as well as pinching effect should be used for timber connections. Regarding multi-storey buildings, the influence of floor panels between two vertical walls should also be considered in the wall models, e.g., using elastoplastic springs or other equivalent methods, to account for the compression deformation in the floor panels. Otherwise, the lateral deflection of the multi-storey walls could be overestimated, resulting in an uneconomical design.

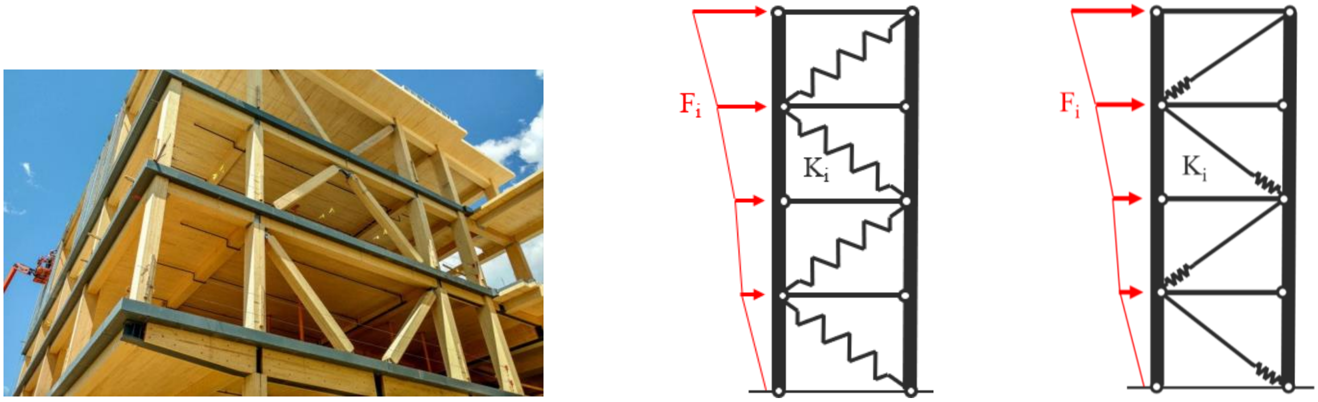
Balloon-type shear walls

In balloon-type construction (Figure 5), walls are continuous over multiple storeys, and floor panels are attached to the sides of the walls at each storey. This construction method alleviates the accumulation of compression perpendicular-to-grain on the floor panels. It also takes advantage of CLT panels that are manufactured up to 20 m in length. Regarding the finite element models, similar to the platform CLT shear walls, CLT panels can be simulated using shell elements, while shear connectors, hold-downs, and vertical joints can be simulated using spring elements, as shown in Figure 1(b). Generally, orthotropic elastic properties are assigned to CLT panels because they are capacity designed, while stiffness and strength are required for the connections. For nonlinear time-history analysis, a hysteretic model capable of stiffness and strength deterioration as well as pinching effect should be used for timber connections. For walls with high gravity loads or a large aspect ratio, the compressive strength of CLT panels needs to be considered in the material model, especially at the wall bottom, so that the pivot point, the moment arm of overturning resistance and hence the lateral resistance and deflection of the walls can be accurately calculated.

Figure 5. Balloon-type CLT building under construction (Courtesy of Nordic Structures).

Braced frames

Braced frames, Figure 6(a), are essentially vertically cantilevered trusses. Because of their high strength and stiffness to resist lateral loads, braced frames are one of the most efficient SFRSs. Unlike braced steel frames, braced timber frames yield and dissipate energy primarily through energy-dissipative connections. Either the diagonal brace assemblies (Figure 6[b]), including a diagonal brace with two end connections, or the two end connections (Figure 6[c]) are modelled with equivalent truss / spring / connector elements that can represent their stiffness, strength, plastic deformation, and hysteretic behaviour. The columns and beams are modelled using elastic beam elements with linear elastic properties because they are capacity designed. If the braced frames do not resist gravity loads, the beams can be modelled using elastic truss elements. The beams are connected to the continuous columns using pin connections. The columns are connected to the ground using pin connections.



(a) (b) (c)

Figure 6. (a)A braced frame building under construction, and schematic diagram of FE model for a 4-storey braced frame with an equivalent element for (b) each diagonal brace assembly or (c) two end connections.

CONNECTION MODELS

Connections in timber structures use a variety of fasteners such as nails, bolts, screws, timber rivets, shear plates, nail plates, split rings, and others. Figure 7 shows the typical hysteresis loops obtained during a reversed cyclic test on a timber connection. The main features shown in Figure 7 include: (a) non-linear connection behaviour; (b) slightly asymmetric loops; (c) indistinct yield point; (d) stiffness degradation with increasing load cycles; (e) relatively fat initial hysteresis loops that imply large amounts of energy dissipation; (f) narrowed loop areas (pinching effect) in the middle of the hysteretic loops after the first load cycle; (g) strength degradation at the same deformation level for repeating loading cycles; (h) strength degradation for larger deformations; (i) relatively high values of ductility. The connection models play a key role in the modelling of the MT structural systems. Typical hysteretic models and backbone curve models suitable for timber connections are summarized in this section. More information can be found in Chapter 7.1 [17] of the modeling guide.

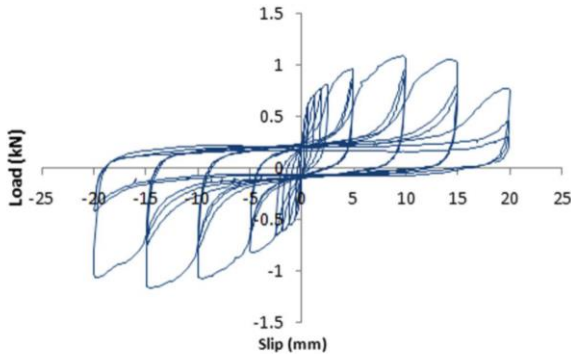
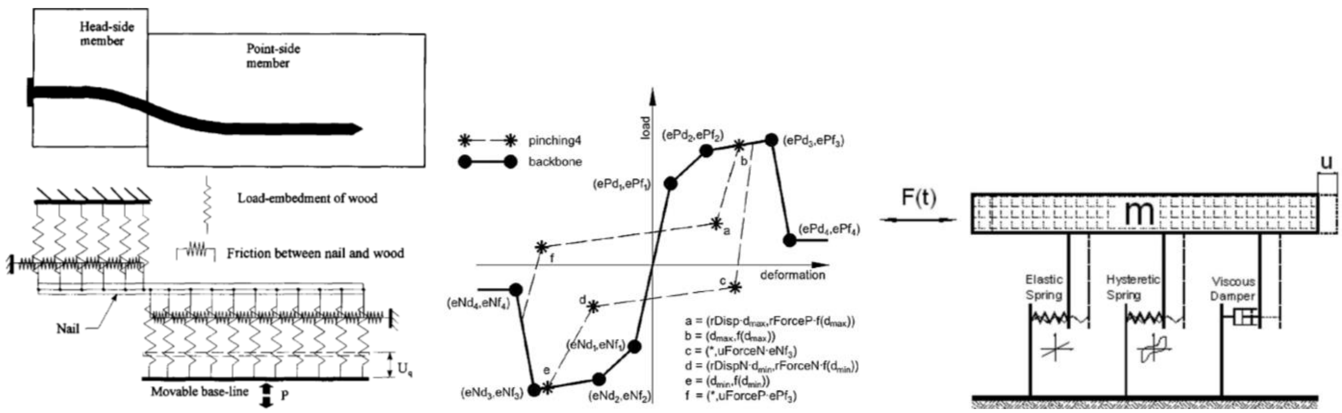


Figure 7 Experimental load-deformation hysteresis loops of a nail connection [18].

Hysteretic models

Nonlinear dynamic analysis involves the explicit modelling of inelastic response, accounting for stiffness and strength degradation, hysteretic energy dissipation, the inclusion of viscous damping and second-order effects, and the selection and scaling of earthquake ground motions. Hysteretic models are the essential parts for such an analysis. The past several decades has seen various types of hysteretic models developed for the dynamic analysis of timber connections and structures. Generally, these models can be categorised into three major types (Figure 8): mechanics-based models, empirical models, and mathematical (phenomenological) models.



(a) (b) (c)

Figure 8. Example of (a) mechanics-based model [19], (b) empirical model [20], and (c) mathematical (phenomenological) model [21].

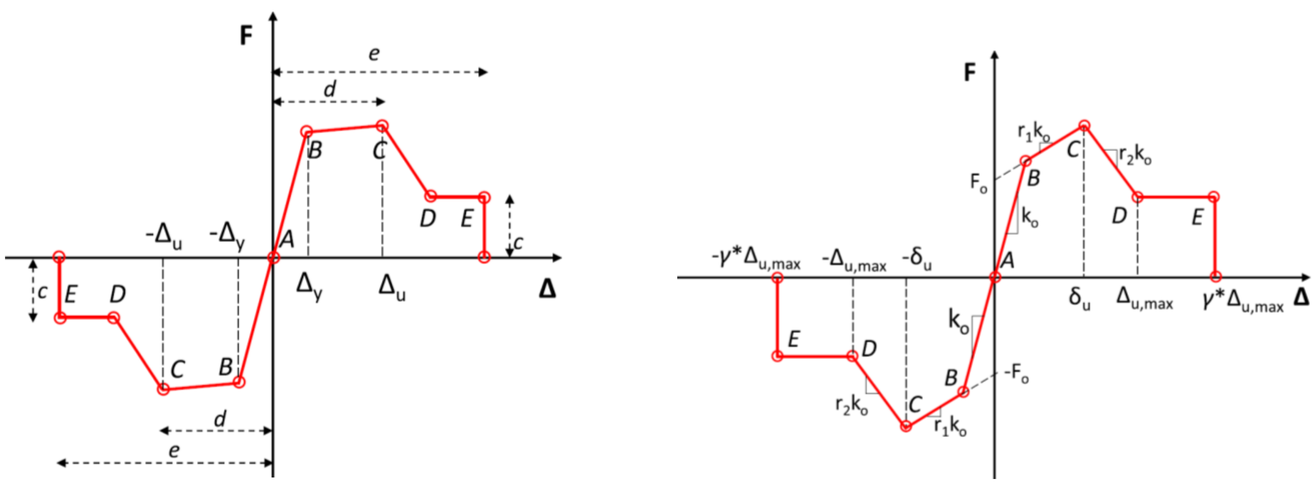
Mechanics-based models represent fasteners and wood members using specific structural elements. For nailed connections, for example, as shown in Figure 8(a), Chui et al. [19] and Foschi [22] modelled the nail and the wood as an elastoplastic beam on a nonlinear foundation. These models rely on the basic material properties of the fastener and the embedment characteristics of the surrounding wood medium. They provide fair accuracy for the hysteresis loops of timber connections. Instead of calibrated parameters, to which it may sometimes be difficult to assign a physical meaning, this approach uses constraints with which engineers are more familiar: moduli of elasticity, yield stress, etc. Such models automatically adapt to any input history, whether force or displacement, and develop pinching loops as the gaps form, which makes the models protocol independent. The more general procedure used in mechanics-based models is more computationally intensive than the fitted tools in other models, since it requires the solution of a nonlinear problem at each time step.

Empirical hysteretic models, also called piecewise linear function models or parameter hysteretic models, are commonly used in structural engineering. They function by specifying a set of rules for loading and unloading paths. These rules usually involve a set of parameters which are calibrated to the observed experimental response of a connection or assembly for a given load or displacement history. There have been a number of attempts to empirically model timber connections under reversed cyclic loading, e.g., the Kivell model, Stewart model, Ceccotti model; Modified Stewart model or MSTEW model, Rinaldin model; and Pinching4 model (Figure 8[b]). For deformations larger than those already occurring in the tested connection, the models follow the envelope or skeleton curve describing the behaviour of the connection under static loading. Empirical models provide good fitting accuracy for the hysteresis loops of timber connections, but do not rely on mechanical properties. Although they do depend on physical parameters, e.g., displacements, forces, and stiffnesses, the model parameters must derive from calibration to existing test results, that is hysteresis loops. This implies that most models can only be used in specified cases where the hysteretic behaviour of timber connections is known. It is also uncertain whether the fitted set of parameters properly represents loops for histories other than the one used in the calibration, given that this loop represents a specific structural response to a corresponding loading history.

Mathematical models are also called semi-physical or phenomenological models. In general, they do not involve a detailed analysis of the physical behaviour of a system through its hysteresis loops; instead, they combine some physical understanding of the hysteretic system with some form of black-box modelling. The past few decades have seen proposals for various mathematical models of hysteresis. One of the most widely accepted is a differential model originally proposed by Bouc and subsequently generalised by Wen and other researchers. This model is known as the Bouc–Wen model and has seen extensive use to mathematically describe the hysteretic behaviour of components and devices in civil and mechanical engineering. It connects the restoring force and deformation through a first-order nonlinear differential equation with unspecified parameters. By choosing suitable parameters, it is possible to generate a large variety of different shapes for the hysteresis loops to account for strength degradation, stiffness degradation, and even the pinching characteristics of an inelastic structure. Foliente modified the Bouc–Wen–Baber–Noori (BWBN) model to characterise the general features of the hysteretic behaviour of timber connections. Figure 8(c) shows the basis of the modified BWBN model, which is the mass-normalised equation of motion for a single degree of freedom system consisting of a mass connected in parallel to a nonlinear hysteretic spring, a linear spring, and a viscous damper. Mathematical models provide good fitting accuracy for the hysteresis loops of timber connections, but do not directly rely on mechanical properties and physical parameters. The model parameters must be calibrated to the test results, that is force and displacement history. Although the computation time is very short, the process of calibrating the parameters may be lengthy. If the experimental displacements do not provide sufficient information, such as pinching or stiffness degradation, the parameters controlling them may not be properly calibrated.

Backbone curve models

For nonlinear static analysis (pushover), the structure is subjected to gravity loads with monotonically increasing lateral loading until reaching the model's maximum capacity to deform. This requires a backbone curve accounting for the elastic and plastic behaviour of timber connections, as well as residual strength and displacement. However, no backbone curve models are specifically available for timber connections. Alternatively, the backbone curve models (Figure 9) developed by ASCE 41 [23], and Koliou et al. [24], which were proposed for light wood-frame shear walls, can be used for timber connections, since the backbone curves of shear walls and nailed connections are similar. The generalised ASCE 41 backbone curve model, Figure 9(a), accounts for strength degradation and residual strength and is defined in terms of elastic and plastic regions. The envelope backbone model of Koliou et al. was proposed by connecting the parameters of the generalised force-deformation relationship to those of the hysteretic model used in the CUREE-Caltech Woodframe project. Figure 9(b) schematically shows the shape of the proposed envelope backbone curve from cyclic data. The parameters that define the shape of this curve are well aligned with a few of the parameters of the hysteretic model. An important aspect of the proposed envelope curve is that it includes residual strength and displacements for the wood-frame shear walls as a factor of the ultimate displacement ($\Delta_{u,max}$).



(a) (b)

Figure 9. (a) Generalised force-deformation relation per ASCE 41, and (b) monotonic backbone curve envelope proposed by Koliou et al. [23].

MATERIAL MODELS

Because of its inherent anisotropic characteristics, the mechanical behaviour of wood depends on the direction of the grain and the load type, as illustrated in Figure 10. Appropriate material models are the fundamental basis of reliable simulations. The constitutive models incorporated in existing general design software packages are often limited, making the software unsuitable for accurately predicting the mechanical behaviour and failure modes of wood-based materials. Some researchers have developed specific constitutive models for wood-based members, e.g., $Wood^{S}$[11] and $Wood^{ST}$ [13]. Typically, a material model is composed of sub-models for describing the elastic properties, strength criterion, post-peak softening for quasi-brittle failure modes, plastic flow, and hardening rule for yielding failure modes, and densification perpendicular to grain. Depending on the modelling complexities, scenarios, and demands, however, different constitutive models with various combinations of the sub-models can be adopted. If the mass timber components are capacity protected without failure or yielding, then only the sub-model for elastic properties is sufficient for the simulation. More information regarding the material models can be found in Chapter 4.1 [25] of the modelling guide.

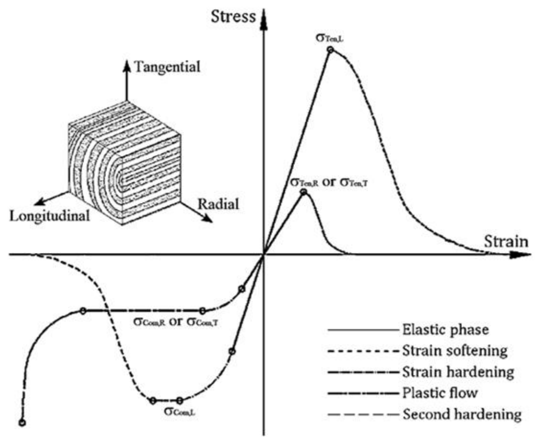


Figure 10. Typical stress-strain behaviour of wood.

As tall or large timber structures are becoming a viable option in the construction industry, the structural elements and connections are becoming more complex, and the corresponding design is beyond the compatibility of general design software packages. Designers can still carry out the design using any tools by making more assumptions. The design as well as the assumptions must be verified by testing, numerical simulation, or both. In such a scenario, general purpose FE software with a comprehensive constitutive model of wood-based material is the first choice for the simulation. A comprehensive constitutive model can predict potential failure modes, including those that may be overlooked in design, providing more reliable analysis results to support the design. With the appropriate constitutive model, the strength, stability, and deflection problems of wood-based members can be investigated and evaluated. The outputs still need to be interpreted carefully using engineering judgment.

ANALYSIS METHODS

The seismic response of timber structures is a complex process, involving many interacting factors, which need to be understood and quantified. The main structural aspects include, but are not limited to: (a) properties of the wood or the engineered wood products used as a structural material, (b) building configuration and structural irregularities, (c) dynamic characteristics of the building (stiffness and mass), (d) stiffness and deformational characteristics of the building, (e) damping and energy-dissipating mechanisms, (f) strength and failure modes of the connections, (g) influence of nonstructural components, and (h) redundancy. Seismic response analysis is a crucial evaluation of timber structures in earthquake-prone areas. There are two main types of static analysis: linear and nonlinear. Nonlinear static analysis is used where a structural system is expected to experience changes in its strength and stiffness properties with varying loads over time. There are different approaches for performing nonlinear static pushover analyses and calculating the target displacement. The two most prevalent in North America are the so-called coefficient method and the capacity spectrum method, while in Europe the N2 method is widely used. Response spectrum analysis is a linear dynamic analysis method which determines the contribution from each natural mode of vibration on structural performance. It provides insight into dynamic behaviour by measuring pseudospectral acceleration, velocity, or displacement as a function of structural period for a given level of damping, thus being accepted as a standard analysis method in many standards. The time-history analysis provides an evaluation of the time evolution of the building response. Generally, two types of time-history analyses can be performed: linear and nonlinear. Both approaches require a numerical model with its characteristics tuned well to represent the lateral resistance mechanism of a real structure, and properly selected and scaled ground motions. Detailed information related to different types and methods of static and dynamic analyses used to quantify the seismic response of timber structures is provided in Chapter 10 [26] of the modelling guide, along with their advantages and drawbacks. It also highlights the specific modelling requirements and considerations for different types of seismic response analyses, along with their suitability for timber structures.

CONCLUSIONS

This paper provides a high-level overview of seismic modelling and analyses of timber structures that is covered in the FPInnovations modelling guide. The goal of the Guide is to assist practicing engineers to apply computer modelling to timber structures, enrich researchers' resources for advanced computer modelling of timber systems, and assisting software companies to identify the existing gaps and upgrade programs accordingly to accommodate advanced computer modelling of timber structures.

ACKNOWLEDGMENTS

This project was financially supported by Natural Resources Canada through the Expanding Wood Use Towards 2025 project and the Green Construction through Wood program. We also acknowledge the financial contribution from Ministère des Forêts de la Faune et des Parcs du Québec. In-kind support provided by NRCan, CWC, AWC, and FII is greatly appreciated. Contributions by more than 100 authors and reviewers of the guide are greatly appreciated.

REFERENCES

[1] Rainer, J., and Karacabeyli, E. (2000). "Wood-frame construction in past earthquakes." In *the World Conference on Timber Engineering*, Whistler, Canada.
[2] Chen, Z., Tung, D., and Karcabeyli, E. (2022). *Modelling guide for timber structures*. FPInnovations, Pointe-Claire, Canada.
[3] Chen, Z., Wiebe, L., and Vecchio, F. (2022). "Structural behaviour and modelling emphases of timber, steel, and concrete structures." in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.
[4] Chen, Z., Reale, V., Kaminski, S., Epp, L., and Stylianou, M. (2022). "Modelling principles, methods, and techniques." in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.
[5] Chen, Z., and Popovski, M. (2020). "Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads". *Engineering Structures*, 208:109916.
[6] Chen, Z., Popovski, M., Jackson, R., Epp, L., and Dlubal, S. (2022). "Mass Timber Structures" in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.
[7] Chen, Z., Popovski, M., and Tung, D. (2023). *Expanding wood use towards 2025: Mass timber diaphragms.* Research report 301015178, FPInnovations, Vancouver, Canada.
[8] Schellenberg, A., Mahin, S., and Fenves, G. (2009). *Advanced Implementaion of Hybrid Simulation*. PEER Report 2009-104, Pacific Earthquake Engineering Research Center, University of California, Berkeley, USA.
[9] Yang, T, Tung, D., Li, Y., Lin, J., Li, K. and Guo, W. (2017). "Theory and implementation of switch-based hybrid simulation technology for earthquake engineering applications". *Earthquake Engineering & Structural Dynamics,* 46(14), 2603-2617.
[10] Kwon, O. (2017). "Multi-platform Hybrid (Experiment-Analysis) Simulations." in *Dynamic Response of Infrastructure to Environmentally Induced Loads: Analysis, Measurements, Testing, and Design*, Sextos, A., and Manolis, G. Eds. Springer International Publishing, Cham, Gewerbestrasse, Switzerland.
[11] Chen, Z., Zhu, Z. and Pan, P. (2011). "Numerical simulation of wood mechanical properties under complex state of stress". *Chinese Journal of Computational Mechanics*, 28(4), 629-634, 640.
[12] Sandhaas, G., van de Kuilen, J., and Blass, H. (2012). "Constitutive model for wood based on continuum damage mechanics." In *the World Conference on Timber Engineering*, Auckland, New Zealand.
[13] Chen, Z, Ni, C., Dagenais, C., and Kuan, S. (2020). "WoodST: A temperature-dependent plastic-damage constitutive model used for numerical simulation of wood-based materials and connections". *Journal of Structural Engineering,* 146(3), 04019225.
[14] Chen, Z., and Popovski, M. (2020). "Material-based models for post-tensioned shear wall system with energy dissipators". *Engineering Structures,* 213, 110543.
[15] Popovski, M., Gagnon, S., Mohammad, M., and Chen, Z. (2019). "Chapter 3 – Structural Design of CLT Elements." in *CLT Handbook (2019 edition)*, Karacabeyli, E. and Gagnon, S. Eds., FPInnovations, Pointe-Claire, Canada.
[16] Karacabeyli, E., and Gagnon, S. (2019). *Canadian CLT handbook*. FPInnovations, Point-Clair, Canada.
[17] Chen, Z., Dolan, D., and Moses, D. (2022). "Light Wood-Frame Structures." in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.

[18] Li, M., Foschi, R., and Lam, F. (2012). "Modeling hysteretic behavior of wood shear walls with a protocol-independent nail connection algorithm". *Journal of Structural Engineering*, 138(1), 99-108.
[19] Chui, Y., Ni, C., and Jiang, L. (1998). "Finite-element model for nailed wood joints under reversed cyclic load". *Journal of Structural Engineering*, 124(1), 96-103.
[20] Mazzoni, S., Mckenna, F., Scott, M., and Fenves, G. (2006). *The Open System for Earthquake Engineering Simulation (OpenSEES) User Command-Language Manual*. Pacific Earthquake Engineering research Centre, University of California, Berkeley, USA.
[21] Foliente, G. (1993). *Stochastic dynamic response of wood structural systems.* Virginia Polytechnic Institute and State University, Blacksburg, USA.
[22] Foschi, R. (2000). "Modeling the hysteretic response of mechanical connections for wood structures." In *the 6th World Conference on Timber Engineering*, Whistler, Canada.
[23] American Society of Civil Engineers - ASCE (2017). *ASCE/SEI, 41-17: Seismic evaluation and retrofit of existing buildings*. Prepard by ASCE, Reston, USA.
[24] Koliou, M., van de Lindt, J., and Hamburger, R. (2018). "Nonlinear modeling of wood-frame shear wall systems for performance-based earthquake engineering: recommendations for the ASCE 41 standard". *Journal of Structural Engineering*, 144(8), 04018095.
[25] Chen, Z., Ni, C., Dagenais, C., and Wang, J. (2022). "Constitutive models and key influencing factors." in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.
[26] Popovski, M., Chen, Z., Hashemi, A., and Mikael, A. (2022). "Seismic Response Analysis." in *Modelling Guide for Timber Structures*, Chen, Z., Tung, D., and Karacabeyli, E. Eds., FPInnovations, Pointe-Claire, Canada.