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MODELLING OF TIMBER STRUCTURES

Zhiyong Chen[1], Dorian Tung[2], Erol Karacabeyli[3]

ABSTRACT: Computer modelling is an essential part in the analysis and design of residential and commercial buildings as well as long-span structures. It is also a valuable tool in the development and optimisation of wood-based products, connections, and systems. A survey shows that practicing engineers are typically unfamiliar with timber structure modelling, and researchers generally lack resources for advanced modelling of timber systems. 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 for supporting the application of numerical modelling on analysis and design of timber structures, and development and optimisation of wood-based products and systems. The guide – Modelling Guide for Timber Structures – covers a wide range of practical and advanced modelling topics, including a comparison (in terms of modelling) among timber, steel, and concrete structures; key modelling principles, methods, and techniques that are specific to timber structures; modelling approaches and considerations for wood-based components, connections, and assemblies; and analysing approaches and considerations for timber structures during progressive collapse, wind, and earthquake events. This paper provides a high-level overview of this guide, with the goal of assisting practicing engineers in application of computer modelling to timber structures, enriching researchers' resources for advanced computer modelling of timber systems; and assisting software companies to identify the gaps and upgrade programs accordingly to accommodate advanced computer modelling of timber structures.

KEYWORDS: Timber structures, digital twins, performance-based design, modelling, analyses, optimisation

1 INTRODUCTION

Computer modelling is an essential part in the analysis and design of residential and commercial buildings as well as long-span structures. It is also a valuable tool in the development and optimisation of wood-based products, connections, and systems. A survey by FPInnovations [1] shows that practicing engineers are typically unfamiliar with timber structure modelling, and researchers generally lack resources for advanced modelling of timber systems. Furthermore, wood analysis and design modules currently implemented in a few structural analysis software packages are usually not suitable for complex or hybrid timber structures. This will hinder the application and development of timber construction given that timber structures increasingly require demonstration of performance or equivalency through computer modelling, regardless of whether prescriptive or performance-based design procedures are used.

A global collaboration (Figure 1), including research institutes, consulting firms, manufactures, software companies, and government and associations, was initiated by FPInnovations in 2020 to develop a guide for supporting the application of numerical modelling on analysis and design of timber structures, and development and optimisation of wood-based products and systems. The guide – Modelling Guide for Timber Structures [2] (web.fpinnovations.ca/modelling) – has been developed by selecting efficient modelling methodologies and analysis methods, and robust evaluation criteria for timber structures: seismic response, wind-induced response, and progressive collapse robustness; and developing 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 code. The guide consists of three parts: Part A – Introduction (in green), Part B – Modelling (in red), and Part C – Analyses (in blue), see Figure 2.

Figure 1: *Locations of more than 100 global collaborators*

[1] Zhiyong Chen, FPInnovations, Canada, zhiyong.chen@fpinnovations.ca
[2] Dorian Tung, FPInnovations, Canada, dorian.tung@fpinnovations.ca
[3] Erol Karacabeyli, FPInnovations, Canada, erol.karacabeyli@fpinnovations.ca

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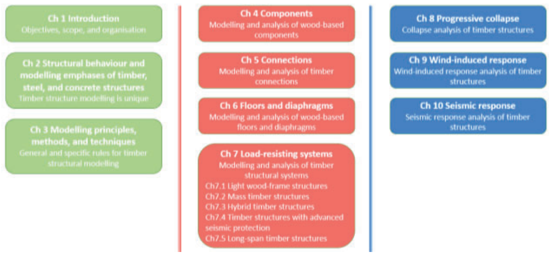

Figure 2: *Organisation of modelling guide*

This paper provides a high-level overview of this 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; modelling approaches and considerations for timber components, connections, floor diaphragms, and load resisting systems; and analysis approaches and considerations for timber structures during progressive collapse, wind, and earthquake events.

2 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. Reinforced concrete (RC) is a composite material that is concrete into which steel reinforcement bars, plates, or fibres have been incorporated, where the two materials work together, with concrete providing the compressive strength, and steel providing the tensile strength primarily. While wood has characteristic anisotropy due to its fibrous structure, which can be considered as producing 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 is brittle, while for wood in compression, the stress-strain relationship is typically nonlinear, and the failure is ductile.

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 steel 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. 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. 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, and any splits effectively remove this capacity altogether. 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.

To model steel elements and connections, material models must simulate the homogeneous, isotropic, and elastoplastic behaviour of steel. 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. 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 of the modelling guide. Selected timber structural systems with analogous ones from steel and concrete are also compared.

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3 MODELLING PRINCIPLES, METHODS, AND TECHNIQUES

3.1 PRINCIPLES

To obtain the best possible analysis results, it is important that engineers follow a formal modelling process that is based on sound engineering and finite element (FE) analysis principles. A typical modelling process includes the following key elements: (a) understanding the structure and planning the modelling process; (b) selecting the software; (c) developing the analysis model; (d) verifying the results; (e) performing a sensitivity analysis; and (f) deciding on the accepted model and results. General and specific principles, in terms of the modelling process, model development, model validation, result verification, model interpretation, and competence are introduced in Chapter 3 of the modelling guide.

3.2 METHODS

Various numerical modelling methods are available for simulating the behaviour of structures under different loading conditions. Mechanics-based modelling, FE modelling, hybrid simulation, and material-based modelling are introduced in the modelling guide. Only the former two are briefly summarised in this paper.

3.2.1 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 FE models. 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.

3.2.2 FE Modelling

In this modelling approach, the major structural components and connections are developed using any FE-type 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.

In the FE modelling approach, the major 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.

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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 the structural models according to their stiffness and deformability characteristics. Nonstructural components, such as gypsum wallboard, provide considerable additional stiffness to lateral load-resisting systems. Engineers must exercise judgment about whether the contribution of nonstructural components should be considered in the model.

3.3 TECHNIQUES

Due to the highly variable anisotropic mechanical properties of wood, this variability has to be accounted for in the design and analysis of timber structures. The stochastic FE method (SFEM) accounts for the uncertainty of a structure that occurs as a result of variations in geometry, materials, or loading condition, thus being one of the best modelling approaches to quantify or predict the influence and sources of randomness in timber structures. Monte Carlo simulation, perturbation method, and the spectral SFEM are the most commonly used and accepted SFEM. Each method adopts a different approach to represent, solve, and study the randomness of a structure. Computational structural design, including parametric analysis, structural optimisation, and form-finding, can influence or enable the exploration of design space. Its application will dramatically improve the efficiency of identifying the best solutions for the structural design of geometrically complex or free-form timber structures.

BIM is a technology-driven integrated digital process that uses intelligent geometric and data models to provide coordinated, reliable information about a project throughout its entire life cycle. With the BIM revolution, the focus has been on the M—modelling: creating accurate and highly detailed models and drawings which represent the design, effectively creating digital twins (Figure 3). However, the building industry does not merely need increasingly more detailed 3D models; it needs a design for manufacture and assembly (DfMA) process to increase design and on-site efficiency while systematically reducing construction change orders.

Figure 3: *Digital twin model of UBC Brock Common*

4 MODELLING OF WOOD-BASED COMPONENTS

4.1 CONSTITUTIVE MODELS AND KEY INFLUENCING FACTORS

Wood is an anisotropic material. Because of its inherent characteristics, the mechanical behaviour of wood depends on the direction of the grain and the load type, as illustrated in Figure 4. Appropriate material models are the fundamental basis of reliable simulations.

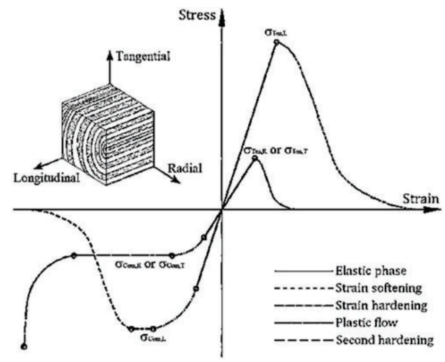

Figure 4: *Typical stress-strain behaviour of wood*

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} and WoodST. 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.

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.

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The mechanical properties of wood change as temperature, moisture, and loading time change. Moreover, growth characteristics such as slope of grain and knots significantly affect the mechanical behaviour of wood-based products. These key influencing factors are discussed in Chapter 4.1 of the guide along with corresponding modelling recommendations.

4.2 STRUCTURAL COMPONENT ANALYSIS

Analyses of timber components under various loads are essential for structural design and product optimisation. Numerous studies have been conducted on traditional wood-based products such as lumber. However, there is limited information on newer wood products such as cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), and other types of composite components.

Of the two approaches used in the analysis and design of timber components, analytical models are very efficient for the specific cases for which the models have been developed. FE methods are capable of handling complex cases and can provide results that are more comprehensive than those provided by analytical methods. Eigenvalue buckling, linear load-displacement, and nonlinear load-displacement analyses are usually adopted to analyse timber components in FE modelling. Linear analysis is the most common method to determine the deformation, reaction, and stresses when an element is in its elastic stage. With engineering adjustment, the lower bound of resistance and the corresponding failure mode of the components can be predicted manually based on the results of linear elastic analysis, for example, stress distribution and the highest stress, for simple cases. Eigenvalue buckling analysis is commonly used to derive buckling resistances and mode shapes for beams and columns. This analysis is best suited for walls, slender beams, and columns where the members are likely to buckle in the elastic range. Nonlinear analysis is capable of predicting the resistance, failure modes, and post-failure behaviour of analysed components, with or without imperfection (e.g., post-buckling analysis). This analysis requires more refined models, or comprehensive material models and specific input. Key considerations, such as imperfection for the post buckling analysis of columns (Figure 5) and beams, for modelling wood-based components under various loading conditions can be found in Chapter 4.2 of the modelling guide.

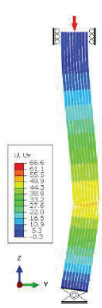

Figure 5: *Deformation (deformation scale factor = 3) of a glulam column under a vertical point load*

4.3 MODELLING PROCESSES AND PROPERTIES OF STRUCTURAL WOOD PRODUCTS

The development of new wood-based products, plus the optimisation of existing products, plays a key role in the expansion of timber construction, especially for taller and larger structures. Manufacture of wood-based products, however, is complex, involving a variety of influencing factors—the properties of the constituents, the structure, and the many parameters of the manufacturing process. Traditional product development and optimisation usually uses trial-and-error laboratory experiments and mill trials, or empirical approaches. While they can offer direct and short-term solutions, experimental studies are generally time consuming and expensive to run; more importantly, they have limitations in providing fundamental understanding. Modelling offers an efficient and cost-effective approach to advancing wood science and industrial composites manufacture. It applies mathematics, physics, and mechanics principles and computer numerical simulation techniques to the field of wood composites. Modelling also helps understand the complex manufacturing process and optimises the product performance by reducing the number and scope of experimental variables.

The production and quality control process are straightforward compared with hot-pressed veneer and strand composites, very few process models are available for lumber-based productions. Many structural models, including empirical models, probabilistic models, and FE models, have been developed for glulam and CLT, to investigate the influence of lumber grades, layup arrangement of graded lumber, species, density, and defects. Several phases of veneer and veneer-based products require careful attention to material and process control as these feed into and affect subsequent steps as well as final product quality and performance. Such processes include log conditioning/heating, peeling, defect and moisture detection, veneer-ribbon clipping, veneer drying, glue application, panel layup, prepressing, and hot-pressing. A series of computer simulation and optimisation models for almost all stages of the process of veneer and veneer-based product manufacture have been developed. FE models are usually used for the mechanical modelling of veneer-based product. Integrative models can be developed on three essential parameter sets for the entire manufacturing process of strand-base products. The first parameter set defines the constituents from which wood composites are made: mainly wood, resin, and wax. The second parameter set defines the structure (the spatial organisation) of the constituents: density, strand orientation, porosity, and contact. The final parameter set concerns major processing steps: strand preparation, drying, blending, forming, and pressing. Various physical models have been developed to simulate strand cutting (from bamboo culms); particulate or strand drying; resin; mat forming and consolidation; and hot-pressing. FE modelling, multiscale modelling, and integrated modelling are used to predict the mechanical properties of strand-based products. Figure 6 illustrates an integrated model for LSL. More detail information can be found in Chapter 4.3 of the modelling guide.

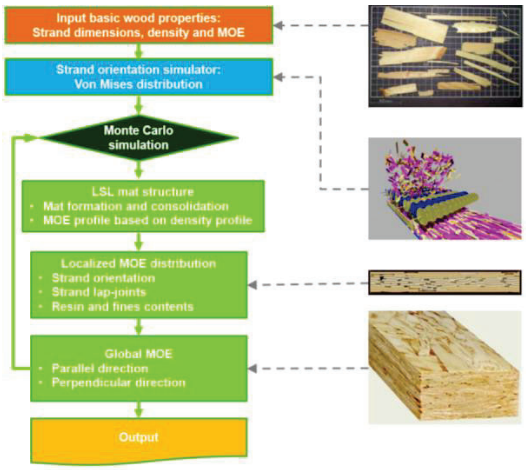

Figure 6: *Schedule diagram of an integrated model for predicting the MOE of LSL*

5 MODELLING OF WOOD-BASED CONNECTIONS

Connections play a crucial role in the integrity and load-resisting mechanism of structures. Well-designed timber connections with mechanical fasteners are usually characterised by highly nonlinear behaviour, strength and stiffness degradation, and pinching effect on their hysteresis loops. All these aspects may pose significant challenges for modelling of timber connections (Figure 7) and how they interact with other elements in the structure.

When modelling timber connections in structures, depending on the purpose of the model, it may be necessary to model the response of the connections, providing upper and lower bounds, particularly for the yielding resistance. These are often built-in to typical backbone curve forms provided in analysis software. When considering modelling stability, it is often useful to implement a post-failure tail to ensure model stability. Where a nonlinear time-history analysis is required, it is also important to properly implement the correct hysteresis form. The main features shown in typical hysteresis loops of timber connections include (a) nonlinear 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, and (i) relatively high values of ductility. Therefore, a hysteretic model capable of predicting stiffness and strength degradation, along with the pinching effect, is desirable for timber connections. During the past several decades, various types of hysteretic models have been developed for dynamic analysis of timber connections and structures. Generally, they can be categorised as three major types: mechanics-based models, piecewise linear functions models, and mathematical models. Chapter 7.1 of the modelling guide discusses the backbone curve and hysteretic models in detail.

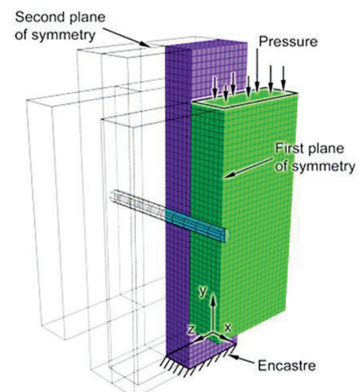

Figure 7: *FE model for bolted connection [3]*

The steel dowel type and glued-in-rod type connections, which involve timber and steel materials, are more complex than the other types of connections composed primarily of steel. Efficient models, e.g., European yield model, have been developed for predicting mechanical properties of ductile failure modes of dowel type connections. However, the brittle failure modes typically can be precited by FE modelling. In such cases, the timber, steel, and contact between them, e.g., gap or glue, must be simulated using proper elements and constitutive models. Figure 8 illustrates modelling examples for dowel type connections.

More information, e.g., the structural behaviour, failure mechanism, design considerations, modelling methods, and key considerations of timber connections can be found in Chapter 5 of the modelling guide.

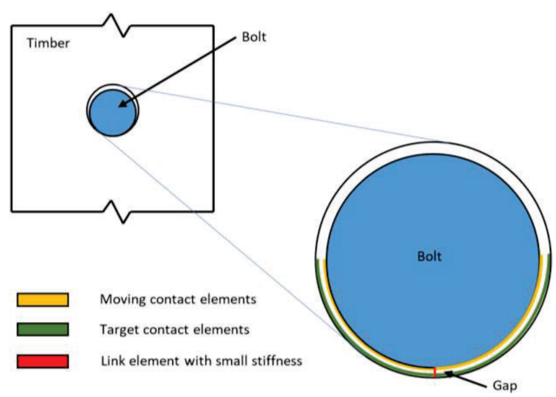

Figure 8: *Example where contact elements are used between fastener and timber*

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6 MODELLING OF WOOD-BASED FLOOR DIAPHRAGMS

6.1 FLOOR AND ROOFS

Timber-based roofs and floors, whether light wood-frame, mass timber, or timber-concrete composite (TCC) systems, are complex structures to analyse despite their relatively simple construction. This is because they are constructed with multiple components and multiple materials that are often connected by mechanical fasteners, leading to semi-rigid connections between components, which is called composite action.

In analysing the structural performance of floor systems, composite beam and ribbed-plate models are available. The ribbed-plate models are typically only used for light wood frame floors to account for its two-way action. There are two main categories of beam models in composite systems: continuous bond models and discrete bond models. The continuous bond models, where the connections are modelled as evenly distributed, include the Gamma method and the Shear Analogy method, among others. The discrete bond models, where the connections are modelled as individual members, include beam models with rigid-perfectly plastic connections or elastic-perfectly plastic connections (also called progressive yielding model, release-and-restore method). Continuous bond models are more suited for composite systems with continuous connections or uniformly distributed connections that are closely spaced, while the discrete bond models are more suited for discontinuous connections. Because of their complexity and efficiency, discrete bond models are usually applied to composite systems with nonuniformly and widely spaced distributed connections, for example, TCC floors.

While most floors and roofs can be designed using the analytical approaches, advanced modelling methods such as FE models can be used for cases beyond the scope of the analytical methods and the system development and optimisation. Framework/truss model (Figure 9) and space-exact element model are two typical FE models for floor systems. More details regarding the analytical and FE models, general rules, and specific consideration for developing FE models for different types of floors are provided in Chapter 6.1 of the modelling guide.

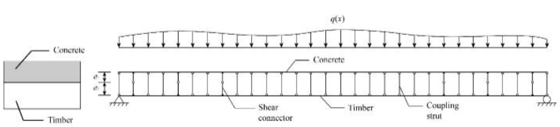

Figure 9: *Framework model*

6.2 DIAPHRAMGS

Diaphragms not only transfer any horizontal load to the vertical lateral load-resisting system (LLRS) but also tie all structural and nonstructural elements together, providing integrity to a building. Several different analysis methods and approaches that can serve to analyse diaphragms include deep beam/girder analogy, shear field analogy, truss analogy, and FE methods. Beam analogy methods provide satisfactory results, as long as the floor is rectangular and does not contain substantial irregularities, such as floor openings, re-entrant corners, and concentrated forces. These influence the load path, leading to stress concentrations, and therefore require more specific designs. The shear field analogy provides a reasonably easy method to analyse wood frame diaphragms with irregularities like openings or re-entrant corners. As the number of irregularities increases, however, this method, based on hand calculations, soon becomes too complex. The assumptions of the shear field analogy are very often violated in real structures. Loads not applied via the framing elements in their axial direction, as well as displacement incompatibilities, cause inconsistencies in the method. The truss analogy can be seen as a compromise between a simple approach like the girder analogy and a sophisticated FE analysis. It allows for irregular geometries and provides a clear force path through all involved members. Complex geometries might need a refined mesh, resulting in a number of different diagonals. Because the forces are introduced as concentrated loads in the nodes, some calculated results (like the axial force in framing members) require post-processing to account for the real force distribution along the member length.

FE analysis of diaphragms provides the most realistic load path and information on the general performance of the diaphragms, but it also requires a high degree of knowledge about the specific software package and a larger number of input parameters. A designer must determine the level of analysis required for the specific diaphragm. For timber diaphragms, this can range from elastic models with homogenous material parameters that have reduced shear stiffness to account for fastener stiffness to orthotropic panels connected with discrete nonlinear links to model the individual fasteners (Figure 10b). Designers need to decide which approach best suits the given problem and what level of accuracy is required. More details on the modelling and design of wood-based diaphragms are presented in Chapter 6.2 of the modelling guide, along with connection options linking diaphragms to lateral load-resisting systems.

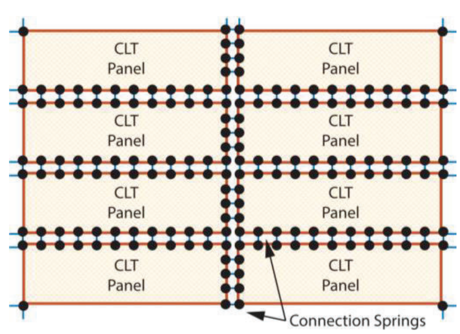

Figure 10: *Discrete panel model with spaced connections [4]*

7 MODELLING OF LOAD-RESISTING SYSTEMS

7.1 LIGHT WOOD-FRAME STRUCTURES

Light wood-frame buildings are constructed using dimensional lumber framing and wood-based sheathing connected to each other with metal fasteners. This type of system has been dominated in timber engineering for a long while and been investigated intensively. Elastic model, plastic models with upper bound method (Kinematic theorem) and lower bound method (static theorem) are the three main analytical models for light wood-frame buildings, the last one has been adopted by many countries' standards to design this system. Regarding advanced FE modelling methods, this system can be simulated using either very detailed models that includes lumber, panels, and nails, or macro-element models where each wall or diaphragm assembly is simulated using an equivalent spring. For both types of models, backbone curve and hysteretic model play a crucial rule in the performance of this system. Generally, mechanics-based models, empirical models, and mathematical models are the three main types of hysteretic models for timber structures. For practical analyses, the shear walls can also be simulated using stick and rotational spring model or equivalent beam model. More information regarding the structural behaviour and modelling considerations can be found in Chapter 7.1 of the modelling guide.

7.2 MASS TIMBER STRUCTURES

Mass timber structures are a viable solution for taller and larger construction. The existing pure mass timber lateral load-resisting systems include platform-type shear walls, balloon-type shear walls, braced frames, and moment frames.

CLT shear walls are the latest lateral load-resisting system of timber structures accepted by codes and standards around the world, while RC shear walls are a system made of other materials that is most similar to CLT shear walls. Unlike RC shear walls, CLT panels are typically capacity-designed, and the connections govern the capacity of the CLT shear walls. CLT panels can be modelled as orthotropic plates, and the connections must be simulated using specific models to represent their stiffness, strength, plastic deformation, and even the hysteretic behaviour, see Figure 11. Braced frames are essentially planar vertically cantilevered trusses. Unlike braced steel frames, braced timber frames yield and dissipate energy primarily through energy-dissipative connections. The diagonal brace assembly or the two end connections must be modelled with equivalent spring elements that can represent their stiffness, strength, plastic deformation, and hysteretic behaviour, while other timber elements can be modelled as elastic truss or beam elements. Moment-resisting frames are rectilinear assemblages of beams and columns, with the beams rigidly connected to the columns. Unlike in moment-resisting frames using steel or concrete, the inelasticity of timber moment-resisting frames is typically concentrated in the beam-to-column connection area due to the nonlinear response of the connections. The beams and columns can be simulated using elastic beam elements, while the connections are modelled using linear or nonlinear spring elements. More information regarding the analytical models and FE modelling considerations for each type of mass timber systems can be found in Chapter 7.2 of the modelling guide.

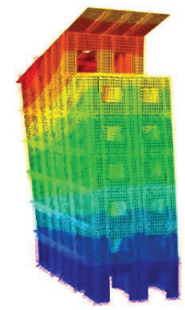

Figure 11: *FE model of a 7-storey CLT building [5]*

7.3 HYBRID TIMBER STRUCTURES

One solution with significant potential for the increased use of wood beyond previous limitations, e.g., building height, involves 'hybrid structures' that integrate wood with different materials. Hybridisation is the process of combining two or more materials to form a system that makes use of the strength of each material and simultaneously overcomes their individual weaknesses.

The gravity load resisting system (GLRS) and LLRS of a hybrid timber structure are typically analysed separately. A main reason for this is to simplify the design by limiting the model contribution of the GLRS to the LLRS, and vice-versa. To conduct a seismic analysis of hybrid timber structures using FE models, it is possible to consider i) the LLRS only; ii) LLRS with connecting GLRS only using appropriate boundary conditions; and iii) both the LLRS and GLRS. For the first approach, one should apply the seismic forces calculated by the ESFP, distributed to the individual LLRS components based on diaphragm flexibility, as a lateral point load at each level. For buildings with core or irregularly shaped LLRSs, the second approach is generally better for determining complex lateral force distribution. The third approach for seismic analysis considers the full building with a complete LLRS, with or without a GLRS, respectively. Special considerations for the design, modelling, and analysis of such structures are provided in Chapter 7.3 of the modelling guide in detail.

7.4 TIMBER STRUCTURES WITH ADVANCED SEISMIC PROTECTION

Timber structures traditionally provided satisfactory seismic performance due to such features as a light weight, high strength-to-weight ratio, structural redundancy, elastic deformation capacity, and the ductility of connections. Nowadays, however, they aim for greater heights and longer spans, resulting in

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challenging seismic designs. Rather than increasing the seismic resistance of a structure, more recent work applies advanced seismic protection technologies to reduce the seismic demand from other structures on those made of timber. Such seismic protection technologies can be grouped into supplemental damping, rocking systems, and seismic isolation.

Modelling Press-Lam systems (Post-tensioned shear walls and moment frames) can involve two main categories of model. The first are spring type models, including the rotational spring models and multi-spring models, with either the rocking connections or the gap opening mechanics simulated using spring elements. The second are material- or component-based models, with geometric and material properties as input. The modelling methods for mass timber structures discussed in Section 7.2 are applicable to timber structures with resilient slip friction joints (RSFJs), but RSFJs are different from common timber connections. The models should properly simulate the RSFJ's flag-shaped hysteresis loops. It is advisable to connect the seismic fuse to another link that accounts for the actual stiffness of the connection between the damper and the remaining timber structural element. The modelling of the seismic isolation plays a key role in the analysis of timber structures with seismic isolation. Typical numerical models include plasticity model for coupled shear behaviour, Bouc-Wen model for coupled shear behaviour, advanced model for elastomeric and lead-rubber bearings, extension of bidirectionally coupled models to friction pendulum behaviour, model for tension-capable double pendulum bearing, and model for triple pendulum bearing. More information regarding mechanics-based modelling and advanced modelling methods is provided in Chapter 7.4 of the modelling guide, along with corresponding recommendations.

7.5 LONG-SPAN TIMBER STRUCTURES

Long-span timber structures are usually adopted by stadiums and bridges. Typical structural forms include trusses, portal frames, arches, suspended structures, and domes. Such long-span structures, like roof applications, are typically designed based on static (strength and stability) analyses, however, dynamics often govern the design of some types of long-span structures, e.g., pedestrian bridges and floors. Free-form systems are also an aesthetically attractive and structurally viable options for long-span timber structures. Dynamic relaxation, among others, is an efficient method in form-finding of free-form structures. The modelling approaches discussed in the above sections, i.e., Sections 7.1 to 7.4, can apply to long-span structures, however, some specific modelling methods or tricks have been developed specifically for long-span timber structures, e.g., how to consider the connections at the end of web members in a truss analysis, how to consider the risk of both in-plane and out-of-plane buckling in an arch analysis, whether the first-, second-, or third-order analysis is more suitable for timber-based suspend structures, and the importance of consideration of geometric imperfections in the analysis of domes. The analysis and modelling of the typical structural types of long-span timber structures are described in detail in Chapter 7.5 of the modelling guide, with corresponding recommendations.

8 PROGRESSIVE COLLASPE

Progressive collapse is a phenomenon initiated by local damage to a structure that propagates throughout the structural system in a chain reaction, leading to the partial or entire collapse of the structure, see Figure 12. Typical design and analysis approaches of progressive collapse include tie forces, redundancy, alternative load paths (ALPs) for static analysis and dynamic analysis, compartmentalisation, and the key element method. In the modelling of both platform-type shear wall systems and post-and-beam systems, the model of connections plays a crucial role and needs load-deformation curves as input. The difference between the platform-type buildings and post-and-beam buildings is in the modelling of the beam-to-column connections where it is needed to quantify their residual shear capacity after they undergo large deformation. Model development and analysis of shear wall systems and post-and-beam systems are described in detail in Chapter 8 of the modelling guide. Key modelling considerations for the progressive collapse analysis of hybrid systems, long-span structures, and prefabricated module structures are also provided.

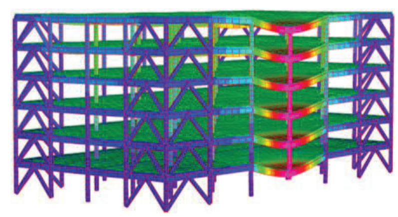

Figure 12: *Progressive collapse analysis of a timber structure*

9 WIND-INDUCED RESPONSE ANALYSIS

Within wind engineering literature and practice, it is generally recognised that wind forces govern the structural design of lightweight and flexible buildings for both safety and serviceability limit states. In general, the action of wind (Figure 13) on tall timber buildings depends on wind hazard, nearby buildings, terrain conditions, building shape, and dynamic structural properties, which is described in the wind loading chain.

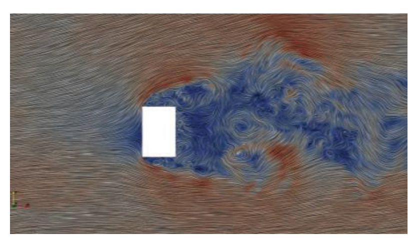

Figure 13: *Wind field around a building*

Wind tunnel techniques are typically used to assess the design wind loads and dynamic wind response of buildings, while computational fluid dynamics (CFD) simulation is adopted for preliminary design and aerodynamic optimisation applications. As with wind tunnel studies, when modelling wind effects using CFD, care must be taken at each step of the wind loading chain. The structural wind-induced response analysis methods mainly include frequency domain analysis method and time domain analysis method. Among them, the frequency domain method uses Fourier transform to transform the wind load into a series of simple harmonic loads, and finally superimposes the response of the structure under each simple harmonic load to obtain the total response of the structure. The disadvantage of this method is that the non-linearity of the structure cannot be considered, and the calculation results are not accurate enough. The time-domain analysis method is to directly use the wind pressure time history of the wind tunnel test or the wind pressure history of the numerical simulation to be used in the calculation model. The response of the structure can be obtained by directly solving the motion equation in the time domain, and the nonlinear response of the structure can be considered. In addition to the above analyses and modelling with key considerations, a framework for the wind design of timber buildings and performance-based wind engineering approaches are also introduced in Chapter 9 of the modelling guide.

10 SEISMIC RESPONSE ANALYSIS

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 (Figure 14) 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 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.

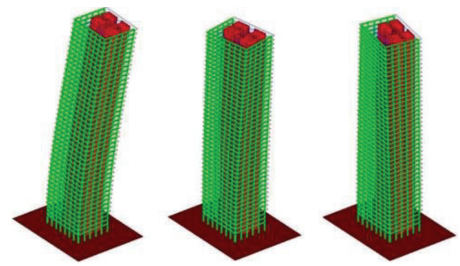

Figure 14: *Mode shapes for the first three modes [6]*

11 SUMMARY

This paper provides a high-level overview of the Modelling Guide for Timber Structures, with the goal of assisting practicing engineers to apply computer modelling to timber structures, enriching researchers' resources for advanced computer modelling of timber systems; and assisting software companies to identify the gaps and upgrade programs accordingly to accommodate advanced computer modelling of timber structures.

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