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Recent research and development in timber engineering in North America

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A review of the recent North American research and development activities in timber engineering is provided including new product development, evaluation of material properties, earthquake engineering of timber structure, reliability and system performance.

1 Introduction

Canada and the US have a strong culture of using wood for residential construction. The light frame wood building is the most common form of timber constructions in North America with over two million housing units built annually. Besides the single-family housing units, the light frame building system is also used in multi-family residential buildings and low-rise commercial structures (see Figure 1).


Figure 1 and 2: North America wood-frame construction

Research and development activities are being conducted in North America to ensure safe and efficient use of the timber resource as construction material. Furthermore as a major international supplier of structural wood products, Canada and the US also have active research programs to develop new products and systems that can address the needs of the global market. This paper describes broadly some of the recent significant research and development activities in North America. Since detailed coverage without omission of some of the activities is difficult, this paper focuses on the thematic research and development area within the field of timber construction in North America including new product development, evaluation of material properties, earthquake engineering of timber structure, reliability and system performance.

2 Material Properties Research

The in-grade testing concept was started in North America in the 1970's and has since been widely accepted throughout the world. This testing philosophy promotes the structural evaluation of the performance of the wood products in the commercial sizes and grades as produced by the manufacturers. It is a very comprehensive approach to perform material properties research given the large number of species, sizes, grades and modes of loading combinations to be considered and the large sample size (N~200) per cell needed to obtain statistically valid data. The advantage is that the data generated represents a more realistic evaluation of the performance of the wood products and allows officials to adopt more accurate design values for the building codes.

In Canada and the US, a comprehensive program on visually graded and machine stress rated dimension lumber (38 mm thick material) was completed in the mid to late 1980's. The resulting database led to the adoption of design values domestically and internationally (Barrett and Lau 1994). Since this in-grade database represents a snap shot of the characteristics resource of the 1980's, more recent efforts in Canada by Forintek Canada Corp. and National Lumber Grades Authorities focused on the establishing procedures for confirmation testing and monitoring of the properties.

In the mid 1990's companies located on the coast of British Columbia, Canada initiated another large scale in-grade study to evaluate the structural performance of their structural products for the Japanese market. The study involved testing Canadian timber in sizes and grades for the Japanese post and beam construction system. Based on this work new grading rules and grades of Canadian Hem-fir were established (Lam et al. 2001 and 2004a).

Based on the design values published in the building codes in North America the design of dimension lumber and structural composite products in bending can sometimes be governed by their shear strength although full size testing rarely shows longitudinal shear failures. In the mid 1990's, US Forest Products Laboratory, Oregon State University, and University of British Columbia carried out independent research studies on this subject. An understanding of the relationship between the shear strength obtained from small notched block shear specimens (~ 62 mm x 50 mm x 50 mm in size) and that of full size members were established. More realistic adjustment factors were introduced into the US standards and Canadian code to resolve the issue.

The influence of sustained loading on the strength of wood products is commonly referred to duration of load effects. It is one of the most important strength adjustment factors for wood products recognized in the Canadian and US building codes. The original concept leading to codification of load duration effects dates back to the studies in the 1950's where researchers from the US Forest Products Laboratory conducted extensive studies to relate the short and long term strengths of clear wood Douglas-fir specimen under center point bending. The famous Madison curve was used as a basis to establish strength adjustment factor in the building codes for many years.

Between the 1970's and 1980's, in concert with the philosophy of in-grade testing, extensive duration of load studies were conducted in Canada and US to further quantify the strength behaviour of dimension lumber under longer term loading (Barrett 1996). Issues including modes of testing (tension, compression, and third point bending tests), sizes (38 mm x 89 mm and 38 mm x 150 mm), material quality, and species (Spruce, Hem-fir, Douglas-fir) were considered by a number of researchers. Various forms of damage accumulation models were also developed and calibrated against test results to describe the observed phenomena. Significant advances to the understanding of long term strength properties of timber products were achieved.

More recently, the influence of load duration on the strength properties of wood products has resurfaced to become an important consideration for the development of new products such as structural composite lumber material. The American Society for Testing and Materials recently developed a consensus based standard to evaluate the influence of load duration and creep on the performance of wood based products (ASTM 2004).

This standard is based on the philosophy of trying to establish performance equivalency between new products and solid wood. An example of a test facility is shown in Figure 2. The testing requires the application of a sustained loading of 90 days at a load level established from 55% of the fifth percentile short term strength of matched specimens. The number of broken pieces is monitored during the test as well as specimen creep rate and relative creep. The product is evaluated as a pass or fail basis to qualify it for use as structural composite lumber. Similar standard is also recognized by the Canadian Construction Materials Centre with additional requirements to test the products after severe soaking and re-drying schedule. The intention of this approach is to establish product performance equivalency compared to solid sawn wood products with additional consideration of simulated on site wet-dry conditions.

Figure 3 and 4: Load duration test facility.

3 Development of Engineered Wood Products

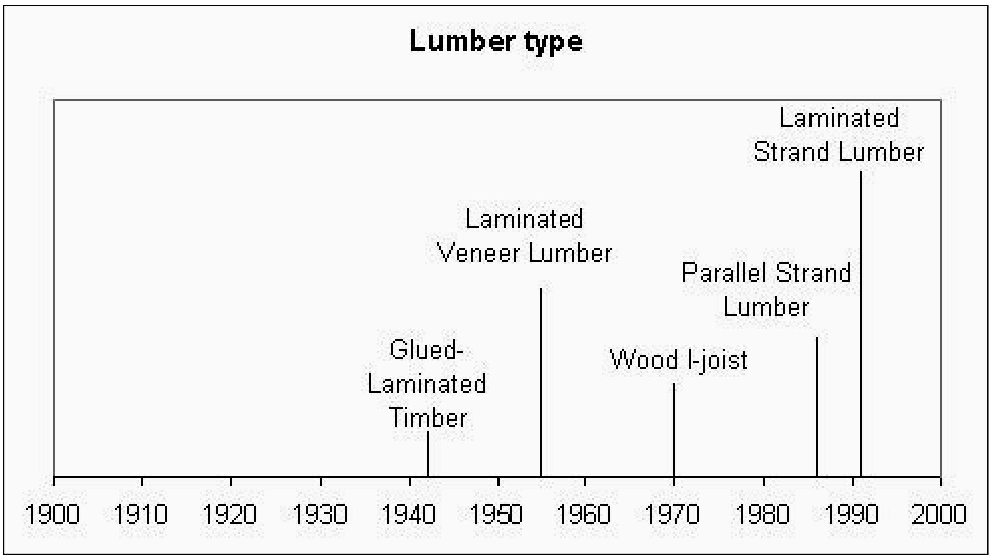
As world population increases and the general living standard of people improves (especially in countries with emerging economy such as China), there is an associated trend for the increase in worldwide demand for wood products. On the supply side, although it is recognized that an amble supply of timber is still available worldwide (considering newly available resources from Russia and South America), there is a shortage of readily accessible high quality timber supply. Therefore there is a need to develop new technologies to improve the harvesting and production process to reduce material losses, and to develop new products from commercial use of smaller diameter, lower quality logs and previously underutilized species and residues. It can be argued that the continual competitiveness of the forest products industry depends on the development of such modern engineered wood products.

A detailed review of modern structural wood products is given by Lam (2001). Engineered wood products, by definition, consist of a broad class of structural composites. These products differ from dimension lumber or sawn timber that is obtained by sawing the logs or cants into individual single solid members. Instead, engineered wood products are made from veneers, strands and flakes that have been formed by peeling, chipping or slicing. These small pieces are arranged or formed for structural purposes and bonded together with adhesives under heat and pressure to make panels, or dimension lumber-like or shaped structural products.

Under this definition, examples of engineered wood products that utilize flakes or veneers to form panels include plywood and oriented strand board. Other composite panel products that may have limited structural applications include particleboard, hardboard, and medium density fiberboard. Structural composite lumber is a generic term used to describe a family of engineered wood products that combine wood veneer or strands with exterior (water resistant) structural adhesives to form lumber-like structural members. In structural composite lumber, the wood veneer or strands are typically aligned with the grain angle of the strands or veneers principally oriented along the length of the member. In some cases, members can also be made with orthogonally arranged layers of flakes. Structural composite lumber products that utilize wood veneer sheets are referred to as laminated veneer lumber while those utilizing wood veneer strands are referred to as parallel strand lumber. Finally structural composite lumber products that utilize flakes are referred to as laminated strand lumber and thick oriented strand board/rim-board.

Engineered wood products in the board sense also include products that are made by bonding individual solid sawn pieces into larger structural members. Some examples include finger-jointed lumber, glue-laminated timber, wood I-joists, and structural insulated panels.

Figure 3 shows the progression in development and commercial introduction of some engineered wood products for building applications.



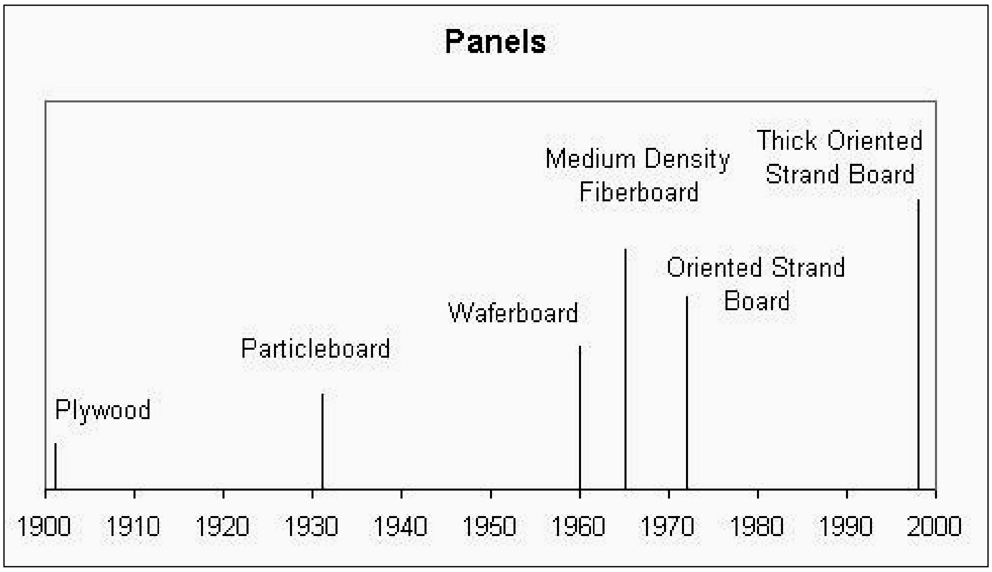


Figure 5 and 6: The progression of development and commercial introduction of engineered wood products for building applications in the last century.

Canadian and the US companies have actively developed new structural composite lumber products and introducing them into the construction industry successfully. Together with glue-laminated beams and I-joists, engineered wood products have been substituted for traditional solid sawn timber components such as beams, headers, columns, and chord members. Moreover, structural composite lumber products are starting to be used in applications typically dominated by steel or concrete (*i.e.* long span commercial roof truss and shell structures). In the future, with the reduced availability of large size solid sawn structural members, engineered wood products will play an even more important role as structural materials.

Oriented Strand Board (OSB) is a product commercially introduced in North America in the 1970's. It aims to replace plywood as a panel product by using underutilized commercial species. The product uses flakes from fast growing hardwood species such as aspen-poplar by bonding them together with phenol-formaldehyde and/or MDI adhesives under heat and pressure to form the members. Typically OSB panels are made in three orthogonal layers. The flakes in the face layers are usually aligned parallel to the long axis of the panel; whereas, the flakes in the core layer are either aligned perpendicular to the long axis of the panel or completely randomly deposited. Typically the core to face ratio is 60:40.

Based on the manufacturing technologies of OSB, thick OSB (>32 mm) can also be made economically. These members can be further manufactured into a deep lumber like products that is suitable for use in some structural applications. Examples of application of the thick OSB include rim-board that forms the perimeter of a floor and short span headers. In rim-board applications, long and deep members can be made where the capacity of the member to transfer vertical loads without crushing or buckling is important. Also the rim-boards are required to be able to transfer lateral loads imposed by earthquakes or high winds. In the short span header applications, the shear strength of the member will be important. In general, the shear strength to bending strength ratio of a product such as thick Oriented Strand Board/rim-board tends to be higher than conventional solid sawn products; therefore, the product may be suitable for use in short span headers applications.

Current development in this area has been extended to the consideration of Oriented Strand Lumber (OSL) where the flakes all three layers are essentially oriented along the long axis of the panel. The resulting product has higher modulus of elasticity and strength than the thick OSB product and is more suitable to span over larger openings. The research and development activities for such products must involve understanding how the manufacturing process can influence the physical and mechanical properties of the material. This is a complicated process where the physics of the heat and mass transfer process, the nonlinear consolidation process, the dynamics of adhesion have an interacting influence on the product attributes. Further complicating the issue are the functions of the former/orientor, the properties and quality of the input resources, the pre- pressing treatment of the flakes, the post pressing treatment of the product, and the mode of application of the product.

4 Performance of Timber Buildings in Earthquake

The primary lateral resisting elements in these structures are the shear wall and horizontal diaphragm systems. The North American wood-frame construction typically composed of framing members sheathed with 1.2 x 2.4 m plywood or oriented strand board panels and connected using nails (Figure 4). The framing members are 38 x 89 mm lumber connected using 76 mm common nails. The spacing of the vertical studs is typically 400 mm. The sheathing panels are connected to the framing members with 50 mm common or spiral nails at a spacing of 150 mm along the panel edges and 300 mm for the interior attachment of the sheathing panel to the frame members. In the US, the panels for shear walls are installed vertically; however, in Canada, horizontally installed panels (with blocking) are also used.

Well constructed wood structural systems have a good performance record against wind and seismic loading due to the high strength to weight ratio of timber as a building material, the system redundancy, and the ductility of connections. However, the structural integrity of wood-frame buildings under the action of natural hazards is not necessarily guaranteed as shown in past earthquakes and hurricanes. The structural and non-structural damages experienced from recent major earthquakes (Northridge 1994 and Kobe 1995) point out some of the inadequacies in the earthquake resistance of wood-frame. Recently major research initiatives were conducted in North America to improve understanding on the seismic response of wood structures (Lam et al. 2002 and 2004b).

Figure 7, 8, 9 and 10: North America wood-frame construction

Figure 11: Failure of the Northridge Meadows apartment complex during the 1994 Northridge earthquake

Canada being a major supplier of structural wood products in the world is also under the threats of catastrophic seismic events. In the University of British Columbia (UBC), a four-year research project entitled "Reliability and design of innovative wood structures under earthquake and extreme wind conditions" was conducted at the between August 1997-July 2001. The total project budget of approximately $1.2 million Canadian dollars was fully supported through a research grant from Forest Renewal British Columbia.

The overall objective of the study aimed to develop fundamental understanding of the static and dynamic structural behavior of two- and three-dimensional frame or panel assemblies made with wood products and subjected to earthquake shaking or wind pressures.

The different phases in the project included: the development of mechanics based nail hysteresis model implemented in structural analysis models of 2-D and 3-D wood-frame systems; the validation of the models with full scale tests using the UBC Earthquake Engineering Laboratory facilities; and the development of framework and tools needed for reliability studies of wood-frame systems under earthquake loading.

Another study of wood light-frame buildings under earthquake loading conditions at the University of BC is the Earthquake 99 Project. The project investigated the seismic performance of narrow Simpson Strong-Walls, conventional shear walls complying with the 1997 Uniform Building Code of the United States, non engineered shear walls were tested in a series of one- and two-storey buildings. A specially designed unidirectional shake table was constructed to accommodate the test specimens with plan dimensions of 6.1 x 7.6 m and an inertial weight of 200 kN. In the test buildings, the primary lateral force resisting system consisted of either four conventional shear walls, 1.2 x 2.4 m, or four Simpson Strong-Walls, 0.61 x 2.44 m, installed at both ends of two exterior walls parallel to the shaking direction (Figure 6). Significant database was developed to guide the design and construction of light-frame wood structures. Some the major findings include the significant contribution of exterior stucco to the seismic resistant in wood-frame construction, the documentation of damage levels in the various tested buildings, and the higher damage in non-engineered buildings sheathed with wall boards.

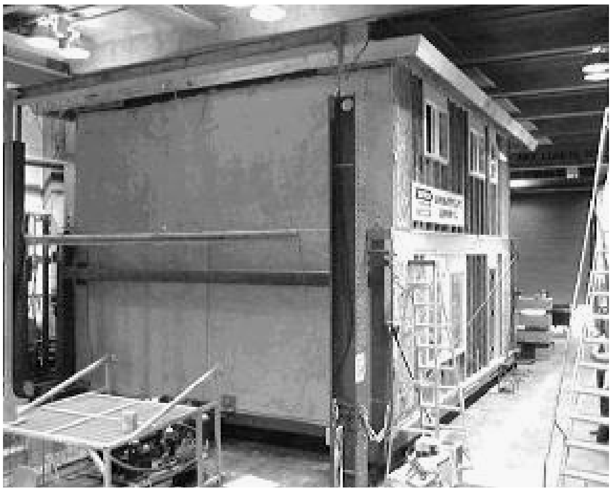


Figure 12: Shake table tests of Earthquake 99 project

In the late 1990's, the CUREE-Caltech (Consortium of Universities for Research in Earthquake Engineering – California Institute of Technology) Woodframe Project was conducted in California as a combined research and implementation project to improve the seismic performance of wood-frame buildings. The project, funded by FEMA (Federal Emergency Management Agency), has five main elements, which together with a management element have the common objectives of advancing the engineering of wood-frame buildings and improving the efficiency of their construction technology for targeted seismic performance levels. The main engineering research components of the project are included in the Testing and Analysis Element managed at the University of California, San Diego. (Lam et al. 2002 and 2004b).

The recent Invitational Workshop on Seismic Testing, Analysis and Design of Woodframe Construction, pointed out the lack of understanding of the seismic behavior of wood-frame structural systems. Very few numerical models capable of analyzing the seismic behavior of three-dimensional wood-frame structures currently exist. Also, only limited experimental data have been generated at the system level. Recognizing these deficiencies, the research strategy of the Testing and Analysis Element of CUREE-Caltech Woodframe Project emphasizes the testing and analysis at both the component level and system level.

As shown in Figure 7, the research plan incorporates five main research tasks (1.1 to 1.5), with shake table tests of large-scale wood-frame systems to be conducted in the early stage of the project. The results of these shake table tests are used to shape the testing and analysis performed in the subsequent tasks. (Lam et al. 2002 and 2004b).

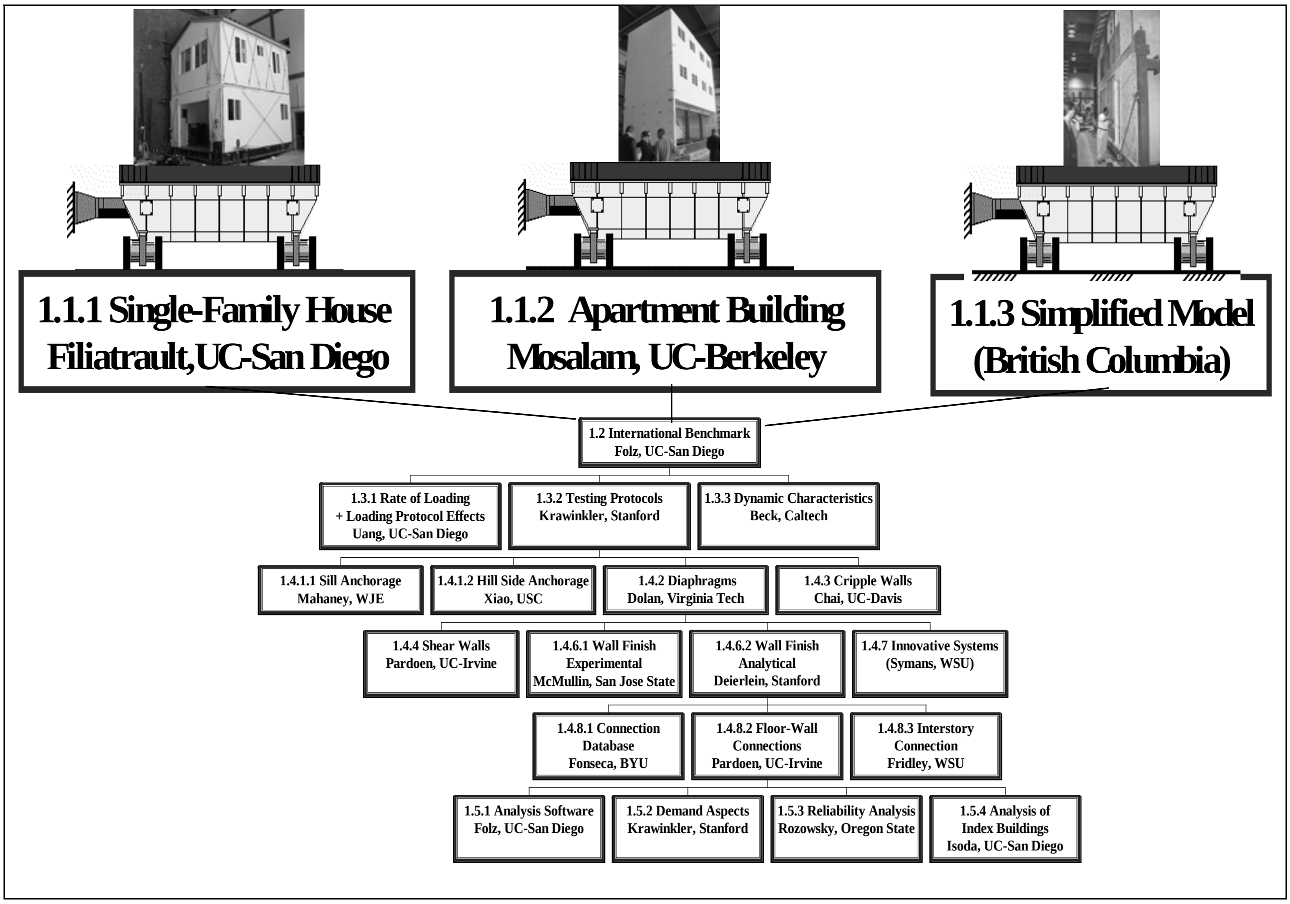


Figure 13: Research strategy for Element 1 of the CUREE-Caltech Woodframe Project

Another organization that has an active research program in the earthquake response of wood structures in Canada is Forintek Canada Corp. covering a wide area of research including the evaluation and modeling of the performance of shear walls, braced frames, connection systems, and innovative building systems.

5 Connections

Study of connections behaviour is one of the key themes in North American timber engineering research community. There are strong interests to adapt innovative European connection techniques for use in North America. For example, there is a need to establish the performance of such connectors with North American solid sawn timber or glue laminated timber. This is particularly true for North American engineered wood products such as parallel strand lumber or laminate strand lumber where database with these state of art connection techniques is unavailable.

Similarly there is a need to study the reverse cyclic load carry capacity of these new connections which is important for seismic design consideration in parts of North America. This point is also true for traditional connections as clear understanding of the energy dissipation characteristics of connections is poor in general.

Furthermore with newly invented engineered wood products, there is a clear need to develop a database on the connection performance of these products for engineering design. Group behaviour of the traditional connectors (such as bolts, dowels, nails, lags crews, and timber rivets) is also a subject of frequent research interest in North America aiming to develop rational design approach which can take into consideration of the various failure modes. Reinforcement techniques to enhance the performance of connections are also investigated by many in North America. The aim is to create stronger and more ductile connection by providing appropriate reinforcement against brittle failure mode such as tension perpendicular to grain and shear.

Finally with the recent advances in CAD-CAM technology to process heavy timber, timber framing and wood-to-wood connections are becoming in vogue in North America. There is a need to develop engineering design rules for these connectors taking into consideration of the method of manufacturing, joint tolerance, connection quality, and the wood material. Efforts are needed to consider the failure mechanism, constitutive relationships, and failure criteria of connections in general and wood-to-wood connection in particular.

6 System Performance and Reliability Assessments

In North American building codes, system behaviour is recognized when three or more parallel members are spaced not more than 600 mm apart. This situation is commonly found in wood frame construction and metal plated wood trusses. System behaviour results from the sharing of loads amongst the members and the composite actions via the contribution of the sheathing elements. Additional interesting research activities are being conducted to expand the concept to fully consider the system behaviour of full scale components such as roofs, floors, and walls. Considerations are also provided towards the system behaviour of full scale model buildings. This is particularly important to understand the load paths and failure mechanism in such complicated but realistic structures.

With improved understanding of the system behaviour, computer models can be developed and validated to represent system performance. The quantification of performance can be established from the perspective of reliability based design philosophy and probability of failure where the stochastic characteristics of the applied loads and the material properties are taken into consideration. Foschi et al. (1989) developed reliability analysis procedures for single members. This type of procedures has been adopted for single member design in the Canadian design code and the US Load and Resistance Factor Design code. Significant effort is need to expand this concept to consider system performance linking the validated computer structural analysis models with reliability analysis procedures.

7 Conclusions

Research and development activities in timber engineering are needed to ensure safe and efficient use of the timber resource as construction material. This paper presented a board overview of the thematic research and development area within the field of timber construction in North America including new product development, evaluation of material properties, earthquake engineering of timber structure, reliability and system performance

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