Performance-Based Approach to Support Tall and Large Wood Buildings: Fire and Seismic Performance

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**PROJECT N° 301011237 – Performance-Based Approach to Support Tall and Large Wood Buildings: Fire and Seismic Performance**

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1 INTRODUCTION

The National Building Code of Canada (NBCC) [1] has traditionally been developed and published as a prescriptive code. The design provisions given in the NBCC have been recognized over the years as “deemed-to-satisfy” solutions that meet its objectives and achieve the minimum performance criteria, which are mostly implicit.

An important shift in design philosophy was introduced in the 2005 edition of the NBCC. It was the first release of the NBCC formatted as an objective-based code, which meant that compliance to the NBCC could be achieved by either complying with the prescriptive provisions given in Division B (also called “acceptable solutions” and the traditional design method) or by using “alternative solutions” that must achieve at least the minimum level of performance required in Division B in the areas defined by the objectives and functional statements attributed to the applicable acceptable solution it was replacing.

Previous reports by FPInnovations [2, 3] aimed at understanding how performance-based building codes around the world address fire safety, investigating and identifying gaps in current knowledge with respect to performance criteria for wood-based building systems as well as developing performance criteria for wood-based design systems meeting the objectives and functional requirements set forth in the National Building Code of Canada. It was found that the intent of the NBCC is mostly in line with requirements of other performance-based building codes, particularly in terms of preventing fires from impacting beyond their point of origin (OS1.2, OP1.2) and collapse of physical elements due to fire (OS1.3, OP1.3) [2]. However, what the NBCC seems to be lacking is relation to directly addressing the safety of occupants and to facilitate emergency response (i.e. fire fighters).

It was also highlighted in the reports that Parts 3 and 9 from Division B of the NBCC are rather prescriptive while others, such as Parts 4 to 6, are rather performance-based [3]. Moreover, performance criteria are not explicitly stipulated in the NBCC. However, a number of prescriptive provisions found in Division B provide some quantitative performance criteria that a design solution should achieve (e.g. fire-resistance rating of structural elements, inter-story drift in wind and seismic design, minimum sound transmission class, etc.). In Canadian performance-based design, it is typically left to the designer to determine suitable performance criteria that meet the objectives and functional statements attributed to the applicable acceptable solutions. While some performance criteria may be generalized, most of them are to be determined based on the actual project scope and proposed design strategies, thus on a “project-specific basis”.

Current prescriptive provisions in the NBCC classify building materials into two (2) distinct groups based on their behaviour, when subjected to the standard test CAN/ULC S114 “Standard Method of Test for Determination of Noncombustibility in Building Materials” [4]. Materials can either be noncombustible or combustible (e.g. wood), whether they pass or fail the test criteria. When classified as a combustible material, it can be used in limited applications within the prescriptive provisions of the NBCC as the classification suggests a fire hazard associated to it. The level of risk is also not differentiated between the degrees of combustibility of materials and incorporates all materials into the same category and a similar fire hazard.

However, as reported by Calder & Senez [5], the historical prescriptive limits imposed on the use of wood products were developed from different knowledge and conditions than today. They have also not changed much over the years since the 1st edition of the NBCC in 1941. Since then, wood products have greatly evolved, as well as the design and construction techniques, and the science knowledge on fire safety and seismic design. These facts and new knowledge should be reflected in modern building codes to remove the historical limits based on the combustibility nature of materials.
and so as to provide a fair and uniform design process to all building materials. This process would allow designing buildings based on their actual performance expectations, rather than designing a building based on an imposed choice of materials deemed to provide an acceptable level of performance, whatever that level may be. Such design process, called a performance-based design, is a relatively new design philosophy.

Lastly, given that typical building designs still mostly rely on prescriptive design provisions, mainly due to academic training of design professionals and Authority Having Jurisdiction, it was reported that there is a need for guides to explain the process of developing, submitting, and ultimately receiving approval for an alternative solution [2, 3].

2 OBJECTIVE

The objective of the current project is to develop a performance-based design process for wood-based design systems that would meet the objectives and functional statements set forth in the National Building Code of Canada.

More specifically, this report discusses the fire and seismic performance of buildings, as identified as a priority in a previous FPInnovations report [3].

3 TECHNICAL TEAM

This project is a research project within FPInnovations’ Advanced Building Systems department, focusing mainly on fire and structural performance attributes. As mentioned in previous FPInnovations’ reports on the topic [2, 3], performance-based design is a design methodology where there is currently a lack of information, technical provisions and performance criteria in the Canadian regulatory system.

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4 WOOD BUILDING SYSTEMS IN THE NBCC

Building systems are classified into two categories in the NBCC which are solely based on a single material chemical property: combustibility. A material is classified as noncombustible if it meets the performance criteria of CAN/ULC S114 [4], or those stipulated in Article 3.1.5.1 of Division B of the NBCC when tested in accordance with CAN/ULC S135 [6]. Based on this classification, there are 2 types of construction explicitly defined in the NBCC: 1) noncombustible construction and 2) combustible construction. When a material is classified as noncombustible, it can be used in any type of construction; a combustible material is to only be used in combustible construction (having numerous prescriptive restrictions such as building height and area), or in limited applications in noncombustible construction.

According to the NBCC, noncombustible construction is “that type of construction in which a degree of fire safety is attained by the use of noncombustible materials for structural members and other building assemblies” [1]. The rationale behind the requirement of noncombustible structural materials is that they cannot contribute to spread or growth of a fire. While both CAN/ULC S114 and CAN/ULC S135 test methods have proven to be efficient at distinguishing fire hazard of materials from their combustibility behaviour, the limited characteristics that both test methods are evaluating do not
provide enough information to understand the actual performance of a material when exposed to real fire conditions, namely for structural elements. For example, aluminum tested per CAN/ULC S114 fulfills the current requirements for a noncombustible material. However, its melting point is below the CAN/ULC S114 exposure temperature (i.e. 750ºC), which could lead to significant and unexpected behaviour when exposed to real fires where temperatures can easily exceed this critical temperature.

It was also demonstrated by White & Ward [7] that all metals, with the exception of gold and platinum, can be expected to ignite in certain conditions. Therefore, if a material ignites (at whatever temperature), flaming will occur and heat could be generated (may not be an exothermic reaction), and should then be “combustible”.

Of utmost importance is the fact that the level of risk implied in the NBCC also is not differentiated between the degrees of combustibility of materials. As such, the current NBCC classification incorporates all materials into the same category and assigns a similar fire hazard, depending on whether or not they pass one of the two test methods referenced above.

On the matter of the concept of “combustibility”, Babrauskas [8] recently made an excellent review of the concept’s evolution in time and noted that it was implemented before quantitative methods of measuring and assessing fire hazard of building components were available. The author mentioned that this is a misapplication of fire safety principles and using variables that express quantitative fire safety principles should now be preferred instead. Among others, evaluating heat release rate of materials in bench-scale and full-scale tests should be performed to calibrate a suitable model that would adequately classify and, most importantly, quantitatively assess fire risk associated with building materials.

Nevertheless, the current edition of the NBCC still refers to the two types of construction, in which different structural systems can be used, whether they are combustible or noncombustible.

Furthermore, Part 4 of Division B of the NBCC requires that buildings, their structural elements and connections be designed to provide sufficient structural capacity and integrity to safely and effectively resist all loads, effects of loads and influences that may reasonably be expected, as well as satisfy serviceability performance criteria such as fatigue under cyclic loads, deflection and vibration, regardless of the type of structural material. In the case of wood structures, their structural design is to be made in accordance with CSA O86 “Engineering Design in Wood” [9].

Part 4 of Division B of the NBCC is mostly performance-based. As such, there are very few limitations for wood structures given in Part 4. Nailed shear walls as well as braced or moment resisting frames with ductile connections have assigned $R_d$ and $R_o$ values, while any other wood-based seismic-force-resisting-system (SFRS) not listed in the NBCC would have the lowest assigned $R_d$ and $R_o$ values ($R_d \cdot R_o = 1.0$), which is quite penalizing when determining the minimum lateral earthquake force. This lower limit is also valid and applicable to any SFRS not listed in the NBCC, whether it is made from masonry, concrete or steel.

Another limiting aspect in the NBCC is related to the severity of the seismic demand (i.e. $I_E F_o S_o(0.2)$). Depending on its value, a wood-based SFRS has height limitations.

It is further stipulated in the NBCC that when it is demonstrated through testing, research or analysis that the seismic performance of a structural system (currently not listed in NBCC) can provide a performance level equivalent or better to that of one of the SFRS listed in the NBCC, then such system can use the corresponding $R_d$ and $R_o$ values. Commentary J of the “User’s Guide – NBC 2010, Structural Commentaries (Part 4 of Division B)” [10] provides guidance for designing such “alternative” SFRS.
4.1 Wood-Frame Construction

Wood-frame construction is the most dominant type of combustible construction for residential buildings in North America. It essentially consists of repetitive small-size structural elements made of dimensional lumber, engineered wood products and structural sheathing. Figure 1 shows typical 6-storey residential wood-frame construction where the walls are braced with nailed OSB structural panels to provide lateral resistance to wind and seismic forces and the floors are made of prefabricated wood I-joists and a nailed OSB subfloor acting as a floor diaphragm.

Given the relatively small dimensions of the structural elements, passive fire protection typically relies on the use of noncombustible or fire-resistance rated gypsum board (i.e. Type X) to provide sufficient fire-resistance to the building components.

Inherent to wood-frame construction is the presence of concealed spaces. Among other things, the risk of ignition and fire spread within these "combustible" cavities needs to be adequately addressed. A number of prescriptive requirements can be found in Part 3 of Division B of the NBCC which attempt to provide an acceptable level of fire safety (i.e. reduce fire risk to an acceptable level). Examples of prescriptive solutions include the use of fire stopping for service penetrations, noncombustible insulation in combustible concealed spaces and automatic sprinklers in spaces of given geometries, etc.

![Figure 1 – Wood-frame construction](image)

While wood-frame construction can achieve a 2-hr fire-resistance rating, and beyond, when tested in accordance to CAN/ULC S101 [11], it is acknowledged that wood-frame construction denotes the minimum performance level of the “combustible construction” category.

Related to seismic performance, nailed shear walls have a ductility-related factor $R_d$ of 3.0 and an overstrength-related factor $R_o$ of 1.7. There is no height restriction when the severity of the seismic demand ($I_E F \sigma_{d(0.2)}$) is lower than 0.35, but becomes limited to 30 m for a demand between 0.35 and
0.75, and further limited to 20 m when the demand is greater than 0.75. At an inter-storey height of 3 to 3.2 m, this type of SFRS becomes limited to mid-rise buildings to a maximum of ± 6-storeys.

4.2 Heavy Timber Construction

Heavy timber construction is defined in the NBCC as “that type of combustible construction in which a degree of fire safety is attained by placing limitations on the sizes of wood structural members and on the thickness and composition of wood floors and roofs and by the avoidance of concealed spaces under floors and roofs” [1].

Table 1 lists the minimum dimensions required to conform to this type of construction; if these dimensions are met then further calculations are not needed to determine an assembly’s fire-resistance. Figure 2 shows an example of a 1-storey grocery store where the roof elements and their supporting beams and columns are made of glue-laminated timber. The roof decking also consists of glue-laminated timber planks.

Heavy timber construction is also allowed in lieu of combustible construction required not to provide more than 45-min of fire-resistance. Due to this allowance, one can interpret that the NBCC assigns a 45-min fire-resistance rating to heavy timber construction, which is untrue.

Figure 2 – Heavy timber construction (Photo: Cecobois)
Table 1 – Heavy timber minimum dimensions, as provided in Table 3.1.4.7 of the NBCC [1]

<table>
<thead>
<tr>
<th>Supported Assembly</th>
<th>Structural Element</th>
<th>Solid Sawn (width x depth) (mm)</th>
<th>Glued-Laminated (width x depth) (mm)</th>
<th>Round (diameter) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Columns</td>
<td>140 x 191</td>
<td>130 x 190</td>
<td>180</td>
</tr>
<tr>
<td>Roofs Only</td>
<td>Arches supported on the tops of walls or abutments</td>
<td>89 x 140</td>
<td>80 x 152</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Beams, girders and trusses</td>
<td>89 x 140</td>
<td>80 x 152</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Arches supported at or near the floor line</td>
<td>140 x 140</td>
<td>130 x 152</td>
<td>-</td>
</tr>
<tr>
<td>Floors, floors plus roofs</td>
<td>Columns</td>
<td>191 x 191</td>
<td>175 x 190</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Beams, girders, trusses and arches</td>
<td>140 x 241 or 191 x 191</td>
<td>130 x 228 or 175 x 190</td>
<td>-</td>
</tr>
</tbody>
</table>

As mentioned in the “User’s Guide – NBC 1995 Fire Protection, Occupant Safety and Accessibility” [12], elements from heavy timber construction are difficult to ignite due to their large cross-section (vs. traditional wood-frame elements) and, once ignited (or subjected to a fire) will resist collapse reasonably well and char at a predictable rate. The guide further mentions that when a building is protected by automatic sprinklers, it is unlikely that a fire would develop to a sufficient magnitude so as to challenge the structural integrity of the heavy timber elements. This fact is recognized in Article 3.2.2.16 of Division B of the NBCC, “Heavy Timber Roof Permitted”, stipulating that a roof assembly in buildings up to 2-storeys in height is permitted to be of heavy timber construction regardless of building area or type of construction required (i.e. noncombustible construction), provided that the building is sprinklered throughout. When this provision applies to a building design, the structural elements in the storey immediately below the roof assembly are also permitted to be of heavy timber construction.

As such, the NBCC recognizes the inherent fire performance of larger structural timber elements, but with parsimony throughout Division B. Nevertheless, heavy timber construction remains classified as a type of combustible construction, along with the implied fire risk hazard and prejudice associated with such a categorization.

The seismic performance of heavy timber construction relies on the level of ductility afforded by the connections. When moderately ductile braced or moment-resisting frames are used, the $R_d$ and $R_o$ factors are assigned as 2.0 and 1.5, respectively. The $R_d$ reduces to 1.5 for connections of limited ductility. It is noted that the NBCC is not clear as to how to achieve the requisite level of ductility. As such, one should carefully read Mitchell et al. [13] for further guidance. Concentrically braced or moment-resisting frames must have ductile connections such as those made with glulam rivets designed in rivet yielding mode. Bolted connections with a small ratio of wood member thickness to bolt diameter are typically considered as limited ductility connections.

Similarly to nailed shear walls, these two (2) types of SFRS have no height restriction when the severity of the seismic demand ($I_gF_{so}S_d(0.2)$) is lower than 0.35. However, it reduces between 15 to 20 m when the severity of the seismic demand is 0.35 or greater, which is quite penalizing. At an inter-storey height of 3 to 3.2 m, such SFRS becomes limited to low-rise buildings of a maximum of ± 4-storeys.
4.3 Hybrid Construction

Hybrid construction is gaining popularity in North America, namely for enhanced serviceability performance attributes such as long-spanning floors, greater acoustic performance and better floor vibration performance. It essentially consists of a combination of mass timber, concrete, masonry or structural steel elements. Figure 3 shows a hybrid type construction where the gravity loads are supported by post-&-beam glued-laminated timber construction and the SFRS consists of reinforced concrete shear walls. An example of a market that would benefit from hybrid construction would be low-rise and large area buildings, such as warehouses and industrial buildings requiring long spans. Figure 4a shows an all-wood panelized roof system where only the supporting columns are made of steel, while Figure 4b shows an hybrid panelized roof system consisting essentially of a steel-frame structure with wood-based structural sheathing to act as the roof diaphragm. This type of construction is, to date, not explicitly defined in the NBCC. As such, if a structural system consists of timber and some other material (concrete or steel), it would be classified as combustible construction and the relevant applicable fire safety prescriptive provisions regarding building height and areas given in Division B of the NBCC should thereafter be followed accordingly.

![Figure 3 – Reinforced concrete and glue-laminated timber hybrid construction](image)

Similarly, a building that would respect all of the prescriptive provisions for noncombustible construction, except that it incorporates a wood structure, would still be classified as combustible construction according to the defined terms in the NBCC. One can argue that the level of fire safety afforded to such “hybrid” type building would most likely be equal or greater than traditional noncombustible construction, namely that using light-weight cold-formed steel structural elements; perhaps this type of building could fit into a new “limited-combustible” category. The fire performance of such systems has been demonstrated through real-scale fire testing conducted at National Research Council Canada [14], where wood-frame construction and cross-laminated timber construction exhibited a performance level equal or greater than cold-formed steel construction (considered as the noncombustible construction benchmark). The fire-resistance of timber-concrete composite floors have also been evaluated from full-scale testing by FPInnovations [15, 16] and were found to perform very well, reaching more than 3 hours of fire-resistance. This performance is significantly greater than the required 2-h fire-resistance rating for tall buildings using noncombustible construction in Division B of the NBCC.
In hybrid construction where the structural frame resisting gravity loads consists of timber beams, columns and decking and the SFRS consists of reinforced concrete vertical shafts or shear walls (as shown in Figure 3), Table 4.1.8.9 of Division B of the NBCC does not impose many height restrictions. As such, one acceptable solution for tall wood buildings would be to use a reinforced concrete SFRS along with its assigned $R_d$ and $R_o$ values.

### 4.4 Mass Timber Construction

This type of construction has not yet been implemented into the present edition of the NBCC, but there is currently discussion at the Canadian Commission on Building and Fire Codes for implementing encapsulated mass timber construction into future editions. The Régie du bâtiment du Québec defines mass timber construction as a “type of combustible construction in which a degree of fire safety is attained by the use of structural elements as well as floors and roofs from wood elements of large dimension, and the elimination of concealed spaces in floors, walls and roofs. Structural elements of this type of construction include solid lumber, glued-laminated timber or structural composite lumber post-&-beam structural system, and a massive slab system of cross-laminated timber or other structural composite lumber elements. All of the aforementioned structural elements shall have fire-resistance ratings greater than those required for the type of heavy timber construction described in Paragraph 3.1.4.6.(1) of Division B of the Code” [18].

One can observe that the definition aims at defining an enhanced category of combustible construction using the same rationale to that of heavy timber construction (i.e. from imposing minimum dimensions and avoidance of concealed spaces) and recognizing the engineering approach for determining the fire-resistance rating of assemblies (vs. the prescriptive deemed 45-min associated to heavy timber construction).
There are mainly two types of mass timber construction:

1) **Mass timber frames**: this system consists essentially of braced frame timber structures, commonly referred to as “post-&-beam” construction. The roofs and floors would consist of lumber or glue-laminated timber decking, or mass timber plates. Figure 5a shows a 1-storey timber braced frame system made from glue-laminated timber beams, columns and roof decking;

2) **Mass timber plates**: this system consists of timber plates used as roofs, floors and walls, in some ways similar to a “plate” or “shell” structure. The structural elements would consist of cross-laminated timber (CLT), nail-laminated timber (NLT), structural composite lumber (SCL), or any other type of wood-based slabs. Figure 5b shows a 3-storey residential construction made from CLT floors, roofs and vertical shaft walls.

While both systems provide inherent robustness regarding lateral loads and fire safety, the economical solution is to combine both systems to optimize the volume of wood of a mass timber plate system and allow for greater flexibility in the floor design plans (i.e. open concept spaces). Using plates as roofs and floors significantly reduces the construction period and essentially eliminates concealed spaces (vs. enclosed cold-formed steel shafts). These plates, which exhibit inherent fire performance, can also be used for solid timber vertical shafts.

From a seismic performance perspective, mass timber frames would be categorized into the current braced or moment resisting frames with ductile connections, along with their respective $R_d$ and $R_o$ values and height limitations.

The latest 2016 Supplement of CSA O86-14 provides design provisions for platform-type CLT construction (mass timber plates made from CLT) not exceeding 30 m in height, or 20 m when the severity of the seismic demand exceeds 0.75. CLT structures designed with energy dissipative connections may use a ductility-related factor $R_d$ of 2.0 and an overstrength-related factor $R_o$ of 1.5.

Should a different type of mass timber plate be used as SFRS (e.g. nail-laminated timber plates or balloon-frame construction), it needs to be designed in accordance with Subsection 4.1.8 of Division B of the NBCC.
5 IDENTIFIED GAPS

Taller and larger wood buildings are nowadays gaining popularity throughout the world. The “race” is on for which country will construct the tallest timber building. However, as reported by Buchanan [19] and many other authors, there are also several challenges related to the use of timber in these new applications. The need to limit wind-induced lateral displacement and building vibration and provide sufficient ductility for seismic design are critical considerations. As for fire safety design, the concepts of designing for complete burnout (based on moveable fuel content), encapsulation to achieve burnout, and performance-based design are important for tall construction. In a previous FPInnovations report [3], similar caveats were highlighted in an attempt to develop suitable performance criteria.

Related to structural performance, a previous FPInnovations report [3] highlighted that there is a need to define performance criteria along with the design objectives for the structural system for each of the loading conditions. Moreover, acceptable damage levels, acceptable risks, and acceptable losses incurred for each performance criteria should be defined. The damage (loss) levels should be expressed in terms of structural damage and/or non-structural damage, and should also be expressed in the form of potential casualties (if applicable), direct financial costs or downtime (time out of service), resulting from the building damage. Lastly, procedures for assessment of the performance (damage) of the structural system under the specified loading condition should be developed and implemented in the NBCC or in materials’ design standard (e.g. CSA O86 for wood).

With respect to fire performance, the same previous FPInnovations report [3] suggested that a performance-based fire design would remove the combustibility of materials technical barrier, while providing a fair design methodology to achieve the requisite level of safety in buildings, regardless of the materials being used. An actual design would therefore be compared to design objectives, functional statements and performance criteria, thus providing harmonization and consistency between building materials.

6 PERFORMANCE-BASED DESIGN PROCESS

As mentioned in the project’s objectives, the intent of the current study is to develop a performance-based design process for wood-based design systems meeting the objectives and functional statements set forth in Division A of the NBCC. The flowchart shown in Figure 6 illustrates a general approach of a performance-based design process (Figure 6).

The proposed approach focuses on the actual outcomes of a given solution (i.e. identify and quantify the level of acceptable damage/risk during and after a major event) as opposed to using prescribed design solutions intended to achieve a certain (and undefined/implicit) outcome.

The approach is mostly inspired by that given in the “International Code Council Performance Code for Buildings and Facilities” [20] (ICPC) and the “International Fire Engineering Guidelines – Edition 2005” [21] (IFEG) jointly developed by the Australian Building Codes Board, National Research Council Canada, the International Code Council and the Department of Building and Housing of New Zealand. These documents were previously identified as useful and relevant sources of information for designers contemplating performance-based design [2]. Additional sources of information are also referenced herein.
6.1 Compliance Method

As stipulated in Clause 1.2.1.1.(1)(b) of Division A of the NBCC, when complying with the NBCC by using an alternative solution, the design shall achieve at least the minimum level of performance required by Division B in the areas defined by the objectives and functional statements attributed to the acceptable (prescriptive) solution(s) it replaces. Note A-1.2.1.1.(1)(b) of the NBCC further details that because the objectives and functional statements are qualitative, it is deemed that the applicable acceptable solutions from Division B exhibiting the lowest level of performance should be considered to establish the minimum acceptable level of performance for demonstrating compliance through an alternative solution.

However, the fundamental question that needs to be asked prior to demonstrating compliance of a performance-based design is: “what are we trying to achieve?” Several questions need to be asked prior to undertaking a performance-based design, more specifically:

- What objective(s) and performance criteria is the design supposed to achieve?
  - Is it aiming to reduce the risk of ignition within a compartment?
  - Does it aim to reduce the risk of fire from spreading in concealed spaces and/or beyond the room of fire origin?
- Is the design aimed at ensuring sufficient structural stability for taller and larger structural frames?
- Is the sound transmission properly limited to limit occupants from excessive noise?
- Does it need to fulfill other objectives concurrently?
In a performance-based design, an alternative solution should not necessarily need to demonstrate a level of performance at least equivalent to a prescriptive acceptable solution (i.e. a comparative approach). The design will need to demonstrate how it ensures the safety of occupants, limits fire spread, and how structural elements will maintain their strength for a necessary period of time, etc. There are prescriptive requirements which are determined qualitatively through a technical consensus of different stakeholders and building experts, and thus difficult/impossible to quantify. In some cases, there are building code clauses that are not necessarily based on science, but on perception and have just been historically accepted. An alternative solution will fulfill the objectives, functional statements, and required performance criteria based on engineering analyses, which were agreed upon as suitable, reasonable and reliable to ensure a safe and satisfactory design (i.e. an absolute approach). Regardless of the relevant building code clauses that are applicable to a given building project, a performance-based design will achieve an adequate and acceptable safety level and it must clearly demonstrate how this is accomplished.

It is noted that the ICCPC does not require that a performance-based design demonstrate at least the same level of performance to that attributed to the prescriptive solutions found in the International Building Code [22].

6.2 Design Process

The ICCPC defines a performance-based design as “an engineering approach to design elements of a building based on agreed upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria” [20].

Performance-based design is a complex process and requires significantly more engineering analysis and judgment than that of a prescriptive design. It is imperative that designers involve the authorities having jurisdiction (AHJs) from the beginning of the design process because the AHJs will ultimately be responsible for approving the alternative solutions.

Moreover, AHJs approving alternative designs also need to fully understand the design process along with the associated objectives, functional statements and agreed-upon performance criteria. In the eventuality where an AHJ is uncomfortable reviewing a given design, for any given reason, it is strongly recommended that an independent and objective peer-review process be performed by external experts having the required qualifications in the appropriate fields of expertise. Obviously, designers proposing an alternative solution should have the proper qualifications for undertaking this complex design process.

Useful information related to the required documentation in support of alternative solutions can be found in Section 2.3 of Division C of the NBCC. Among others, a Code analysis outlining the applicable objectives, functional statements and acceptable solutions as well as the analytical methods, rationales and limitations used to demonstrate that the alternative solutions achieve at least the requisite level of performance should be documented.

Lastly, given the complexity of a performance-based design, advanced computer modeling will most likely be required. Numerous mathematical models and engineering tools are available for the designers and Authorities Having Jurisdiction (AHJs). It is noted that although no model can be fully perfect, they are very useful in providing detailed information for an expected design scenario. The use of commercial software packages can be challenging as they require expert knowledge and experience for their proper and effective use, as well as significant efforts in entering required data and long computational time. It is thereby the responsibility of the designer to fully understand the
limitations of each model when using them in support of a performance-based design. Additional information about computer modeling is given in Section 7 of this report.

6.2.1 Project Scope

A proper understanding of the building characteristics and normal service conditions is required upfront before undertaking any further engineering analysis. NFPA 5000 “Building Construction and Safety Code” [23] stipulates that general building characteristics and assumptions used in a performance-based design shall be clearly stated and shown as realistic and sustainable.

6.2.2 Objectives

As mentioned in the ICCPC, the purpose of a performance-based design is to provide appropriate health, safety, welfare, and social and economic value, while promoting innovative, flexible and responsive solutions that optimize the expenditure and consumption of resources. A performance-based design should demonstrate that it can limit property damage from events that are expected to impact buildings and structures.

A design conforming to the NBCC should address the following four objectives (OS, OH, OA and OP), as defined in NBCC [1]. Each objective is further refined through the establishment of sub-objectives, which can be found in Parts 2 and 3 of Division A of the NBCC.

A fifth (5th) objective (OE) could also be considered, mainly related to excessive use of energy in buildings as defined in the National Energy Code for Buildings [24].

6.2.3 Functional Statements

The 2015 NBCC lists a total of 55 functional statements in Division A, Volume 1, labelled from F01 to F100 (of which some are not currently determined/assigned). A functional statement describes qualitatively a function of the building, or part of the building, that a particular requirement helps achieve.

Each prescriptive provision found in Division B of the NBCC is linked to one or more objectives, and to one or more functional statements. Objectives and functional statements are always paired together; this pairing helps define what needs to be done (function) and why it should be done (objective). In other words, a building must do “this” (function) in order to meet “that” (objective).

Relatively new since the publication of the 2005 objective-based NBCC are the intent statements. They are explanatory information aimed at explaining, in plain language, the basic thinking behind each prescriptive provision contained in Division B of the NBCC and thus providing greater flexibility to a designer wishing to develop a new method or product that is not explicitly described or covered in the NBCC (i.e. an alternative solution). The intent statements for the 2015 NBCC were not yet available, at the time of this report, but the 2010 NBCC intent statements are still available and accessible online.

Figure 7 illustrates the intent statements attributed to Sentence 3.1.5.1.1(1) of Division B of the 2010 NBCC, directly taken from http://codes-guides.nrc.ca/IA/10NBC/intentframe.html [25]. The Sentence stipulates that a building or part of a building required to be of noncombustible construction shall be constructed with noncombustible materials. While the intent of this Sentence may appear obvious, other prescriptive code provisions are not always obvious. Consulting these statements attributed to certain provisions can clarify their actual intent to potentially limit misinterpretation by code users.
6.2.4 Performance Criteria

A performance-based design should, as mentioned previously, not necessarily need to demonstrate a level of performance at least equivalent to the prescriptive acceptable solution(s) (i.e. a comparative approach). Depending on the design objectives, an alternative solution would likely fulfill the objectives and required performance criteria based on engineering analysis (i.e. an absolute approach), which were agreed upon as suitable, reasonable and reliable to ensure a safe and satisfactory design. While some performance criteria may be generalized, most of them are to be determined based on the actual project scope and proposed design strategies, thus on a “project-specific basis”. Every building and site is unique (although there can be similarities) and its design and evaluation will thereby be unique.

It is also noted that performance criteria are typically not explicitly stipulated in prescriptive and performance-based building codes. Therefore, a performance-based design relies on the designer to determine suitable performance criteria that would meet the objectives and functional statements attributed to the applicable acceptable solutions. As mentioned previously in this report, it is imperative that AHJs be involved from the beginning of the performance-based design (i.e. alternative solution) as ultimately, they will be responsible for its approval.

The ICCPC provides four performance groups (PGs) based on building use and occupancy classifications, the associated risk factors and the importance of a building to a community, as summarized in Table 2. One can observe the parallel between the PGs and the Importance Categories currently used in Part 4 of Division B of the NBCC when performing a structural design (Low, Normal, High and Post-Disaster), which could serve as a “Canadian classification”. The PGs aim at identifying the minimum performance level of buildings through a relationship between the magnitude of an event and the maximum tolerated level of damage, as shown in Table 3. It can be observed that buildings classified as PG IV (i.e. those typically assigned with a Post-Disaster importance category in the NBCC) cannot be subjected to a significant damage level (moderate or mild), regardless of the event magnitude due to their importance of remaining fairly operational.
The maximum level of damage to be tolerated, as defined in the ICCPC, can be summarized as follows [20]. Further details can be found in Chapter 3 of Part I of the ICCPC in terms of structural damage, nonstructural systems, occupant hazards, overall extent of damage and hazardous materials.

- **Mild damage**: no structural damage and is safe to occupy. Nonstructural elements needed for normal usage of the building and emergency operations are fully operational. Little to none minor injuries to occupants and very low probability of life loss. Overall damage is minimal in extent and minor in cost. Minimal hazardous materials released to the environment.

- **Moderate damage**: moderate and repairable structural damage and some delay in re-occupancy can be expected. Nonstructural elements needed for normal usage of the building are fully operational, although cleaning and repair may be needed. Emergency systems remain fully operational. Moderate injuries to occupants, both in numbers and in nature. Low probability of single life loss and very low probability of multiple life loss. Overall damage may be locally significant, but is generally moderate in extent and cost. Some hazardous materials are released to the environment, but the risk to the community is minimal. Emergency relocation is unnecessary.

- **High damage**: significant and possibly repairable structural damage and significant delays in re-occupancy can be expected. Nonstructural elements needed for normal usage of the building are significantly damaged and inoperable. Egress routes may be impaired by light debris. Emergency systems may be significantly damaged, but remain operational. Locally significant injuries to occupants, with a high risk to life, but generally moderate in numbers and in nature. Moderate probability of single life loss and a low probability of multiple life loss. Overall damage may be locally total and generally significant, but is generally moderate in extent and cost. Hazardous materials are released to the environment with localized relocation needed for buildings in the immediate vicinity.

- **Severe damage**: substantial structural damage, but all significant components continue to carry gravity loads. Repair may not be possible and building is not safe for re-occupancy. Nonstructural elements needed for normal usage of the building may be completely nonfunctional. Egress routes may be impaired. Emergency systems may be substantially damaged and nonfunctional. High number of significant injuries to occupants, with a significant risk to life. High probability of single life loss and a moderate probability of multiple life loss. Overall damage may be total. Significant hazardous materials are released to the environment with relocation needed beyond immediate vicinity.
Table 2 – Performance groups, as provided in Table 303.1 of ICCPC [20]

<table>
<thead>
<tr>
<th>Performance Group (PG)</th>
<th>Use and occupancy classifications for specific buildings or facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Buildings and facilities that represent a low hazard to human life in the event of failure, including, but not limited to:</td>
</tr>
<tr>
<td></td>
<td>1. Agricultural facilities.</td>
</tr>
<tr>
<td></td>
<td>2. Certain temporary facilities.</td>
</tr>
<tr>
<td></td>
<td>3. Minor storage facilities.</td>
</tr>
<tr>
<td>II</td>
<td>All buildings and facilities except those listed in PGs I, III and IV.</td>
</tr>
<tr>
<td>III</td>
<td>Buildings and facilities that represent a substantial hazard to human life in the event of failure, including, but not limited to:</td>
</tr>
<tr>
<td></td>
<td>1. Buildings and facilities where more than 300 people congregate in one area.</td>
</tr>
<tr>
<td></td>
<td>2. Buildings and facilities with elementary school, secondary school or day care facilities with a capacity greater than 250.</td>
</tr>
<tr>
<td></td>
<td>3. Buildings and facilities with a capacity greater than 500 for colleges or adult education facilities.</td>
</tr>
<tr>
<td></td>
<td>4. Health-care facilities with a capacity of 50 or more residents but not having surgery or emergency treatment facilities.</td>
</tr>
<tr>
<td></td>
<td>5. Jail and detention facilities.</td>
</tr>
<tr>
<td></td>
<td>6. Any other occupancy with an occupant load greater than 5,000.</td>
</tr>
<tr>
<td></td>
<td>7. Power-generating facilities, water treatment for potable water, wastewater treatment facilities and other public utilities facilities not included in PG IV.</td>
</tr>
<tr>
<td></td>
<td>8. Buildings and facilities not included in PG IV containing sufficient quantities of highly toxic boundaries, gas or explosive material capable of causing acutely hazardous conditions that do not extend beyond property.</td>
</tr>
<tr>
<td>IV</td>
<td>Buildings and facilities designated as essential facilities, including, but not limited to:</td>
</tr>
<tr>
<td></td>
<td>1. Hospitals and other health-care facilities having surgery or emergency treatment facilities.</td>
</tr>
<tr>
<td></td>
<td>2. Fire, rescue and police stations and emergency vehicle garages.</td>
</tr>
<tr>
<td></td>
<td>3. Designated earthquake, hurricane or other emergency shelters.</td>
</tr>
<tr>
<td></td>
<td>4. Designated emergency preparedness, communication, and operation centers and other facilities required for emergency response.</td>
</tr>
<tr>
<td></td>
<td>5. Power-generating stations and other utilities required as emergency backup facilities for PG IV buildings or facilities.</td>
</tr>
<tr>
<td></td>
<td>6. Buildings and facilities containing highly toxic gas or explosive materials capable of causing acutely hazardous conditions beyond the property boundaries.</td>
</tr>
<tr>
<td></td>
<td>7. Aviation control towers, air traffic control centers and emergency aircraft hangars.</td>
</tr>
<tr>
<td></td>
<td>8. Buildings and facilities having critical national defense functions.</td>
</tr>
<tr>
<td></td>
<td>9. Water treatment facilities required to maintain water pressure for fire suppression.</td>
</tr>
<tr>
<td></td>
<td>10. Ancillary structures (including, but not limited to, communication towers, fuel storage tanks and other structures housing or supporting water or other fire suppression material or equipment) required for operation of PG IV structures during an emergency.</td>
</tr>
</tbody>
</table>
Table 3 – Maximum level of damage to be tolerated, as provided in Table 303.3 of ICCPC [20]

<table>
<thead>
<tr>
<th>Magnitude of Design Event</th>
<th>Performance Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing Magnitude of Event</td>
<td>I</td>
</tr>
<tr>
<td>Very Large (Very Rare)</td>
<td>Severe</td>
</tr>
<tr>
<td>Large (Rare)</td>
<td>Severe</td>
</tr>
<tr>
<td>Medium (Less Frequent)</td>
<td>High</td>
</tr>
<tr>
<td>Small (Frequent)</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

According to the ICCPC, the magnitude of event can be defined, quantified or expressed either deterministically or probabilistically in agreement with the best current practice and as recognized in authoritative documents. As an example, climatic loads in the NBCC are categorized based on the probability of exceedance per year [10], where wind and snow loads are based on a 50-year return period and seismic loads are based on a return period of 2500 years.

In the end, a performance-based design should demonstrate a high confidence level that the maximum level of damage to be tolerated will be met, in terms of tolerable limits and under varying conditions, as well as through an iterative process to evaluate the impact of certain events and their magnitude on various mitigation features planned in the design.

### 6.2.5 Design Scenarios

As the building design evolves, the design team (architects, engineers, AHJs, etc.) should incorporate features which are expected to achieve the requisite level of performance and safety. To challenge the robustness of a performance-based design, various design scenarios are to be developed and selected for evaluation (i.e. various fire design scenarios, various return periods for wind and earthquake loads, acceptable damage levels, etc.).

Additional design scenarios may need to be developed in the event that the selected scenarios do not achieve the required performance criteria. As mentioned previously in this report, a performance-based design is an iterative process.

### 6.2.6 Design Strategies

Design strategies should be determined to fulfill the objectives, functional statements and performance criteria already identified in the previous steps of a performance-based design. Given that this report discusses only the fire and seismic performance of buildings, the design strategies referenced herein focus on these two design objectives. Additional strategies would most likely be required to fulfill other design objectives.
6.2.7 Evaluate Strategies

The ICCPC stipulates that design approaches used in a performance-based design shall utilize authoritative documents and design guides to demonstrate that designs are based on applicable and valid technical and scientific methodologies.

According to the ICCPC, an authoritative document is defined as “a document containing a body of knowledge commonly used by practicing architects or engineers. It represents the state of the art, including accepted engineering practices, test methods, criteria, loads, safety factors, reliability factors and similar technical matters. The document portrays the standard of care normally observed with a particular discipline. The content is promulgated through an open consensus process or a review by professional peers conducted by recognized authoritative professional societies, codes or standards organizations, or governmental bodies” [20].

Several verification methods were identified and described in a previous report by FPInnovations [2]. Among others, design guides from the Society of Fire Protection Engineers (SFPE), ISO Standards related to fire safety engineering as well as foreign performance-based codes (Australia, New Zealand, Scotland, Japan and the ICCPC) were detailed and would most likely be valid authoritative documents to support the evaluation of a performance-based design in Canada.

Furthermore, given that the objectives of the current prescriptive fire safety provisions found in Division B of the NBCC are consistent with the concepts presented in NFPA 550 “Guide to the Fire Safety Concepts Tree” [26], the latter could also be used to facilitate the development of performance-based design.

6.3 Fire Engineering Design

Subsection 6.2 provided a general overview of a performance-based design, while giving insight and specific characteristics with respect to structural and fire engineering design. This Subsection 6.3 specifically relates to fire safety engineering and provides further details and information.

6.3.1 Design Process

The first step, as outlined in Subsection 6.2 of this report, relates to defining the project scope. According to the IFEG, the building characteristics should include the building occupancy, its location (proximity to neighbouring buildings, to other hazards, fire stations, etc.), its size and shape, the type of structural system and the interior finish materials (including the presence of concealed spaces, service penetrations, vertical shafts and exit stairs, etc.), as well as any other related hazards such as dead-end corridors, unusual means of egress, location of hazardous materials, potential ignition sources and fuel load characteristics. Information about regular maintenance and use of the fire preventive and protection measures should also be provided.

With respect to fire safety, the assumed number, profile and response of occupants should be documented (age, gender, mobility, sensitivity/reactivity to audible/visual cues, etc.). The location of occupants within a building, at any time, and their displacement changes with time during normal use and emergency events depends on the interaction of a variety of parameters related to the characteristics of the building and the occupants, the fire safety management system proposed for the building, and the development of the fire.
Figure 8 represents the general approach applicable to a fire engineering process, as given in ISO/TR 13387-1 “Fire Safety Engineering - Part 1: Application of fire performance concepts to design objectives” [27]. Once a qualitative design review is done (i.e. objectives, functional statements, performance criteria are identified), the design can be evaluated and quantified against the performance criteria, typically through an iterative process until a satisfactory solution is found.

As stipulated in ISO 23832 “Fire Safety Engineering – General Principles” [28], a standardized method should be used to identify a manageable group of design scenarios for analysis. All interested parties, including AHJs, should be consulted to ensure that all relevant design scenarios are considered. Each design scenario being considered should be clearly identified and all its features related to fire safety should be described so that the essential features of the design are readily identifiable for the purposes of the analysis and future reference [21].

While a quasi-infinite set of design scenarios can be developed, NFPA 5000 [23] requires that design fire scenarios shall include, but not be limited to, at least the following eight scenarios:

1. **Scenario 1**: occupancy-specific scenario representative of a typical fire for the occupancy, clearly detailing the occupancy, number and location of occupants, room size, contents and furnishings, fuel properties and ignition sources, ventilation conditions as well as the first item ignited and its location.

2. **Scenario 2**: ultra-fast-developing fire in the primary means of egress, with interior doors open at the start of the fire to assess the impacts related to a reduction in the number of available means of egress.

3. **Scenario 3**: fire initiating in a normally unoccupied room that potentially endangers a large number of occupants in a large room or other area to assess the impacts related to the migration of a fire into the space than can, potentially, hold the greatest number of occupants in the building.
4. **Scenario 4**: fire initiating in a concealed space (wall or ceiling) adjacent to a large occupied room to assess the impacts related to a fire originating in a concealed space that does not have either a detection system or suppression system and then spreading in the room within the building that can, potentially, hold the greatest number of occupants.

5. **Scenario 5**: slow-developing fire shielded from the fire protection system, in close proximity to a high occupancy area to assess the impacts related to a relatively small ignition causing a significant fire.

6. **Scenario 6**: most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building to assess the impacts of a rapid-developing fire with occupants present.

7. **Scenario 7**: exterior fire exposure to assess the impacts related to a fire starting at a location remote from the area of concern and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area.

8. **Scenario 8**: fire originating in ordinary combustibles in room or area which each passive or active fire protection system or fire protection feature independently rendered ineffective to assess the impacts related to fire protection systems or features, considered individually, being unreliable or becoming unavailable. It is noted that this 8th scenario is not required when the level of reliability and the design performance of fire protection systems or features are judged acceptable by the AHJ.

While the eight scenarios above may be challenging for a structural system, they somewhat aim at evaluating the safety of building occupants. When developing design fire scenarios that would be more challenging from a structural integrity perspective, ISO/TS 24679-1 “Fire Safety Engineering – Performance of Structures in Fire” [29] recommends that a combination of the following factors be considered to determine different design fire scenarios:

1. Type of fire: its location with respect to the structural elements, its size (localized, fully-developed, traveling, etc.).
2. Distribution and type of fuel content (i.e. combustible materials).
3. Ventilation conditions: impact on the severity and duration of a fire based on the availability of oxygen due to windows, doors, openings, etc.
4. Status of the active fire protection systems and passive fire safety measures, as well as their performance and reliability.

### 6.3.2 Performance Criteria and Performance Assessments

A lot of research has been conducted throughout the world in recent decades in regards to fire safety engineering. Among others, Canadian researchers have conducted many studies and published various scientific articles on the subject since the early 1970s. Hadjisophocleous et al. [30] have undertaken a thorough literature review of performance-based codes and listed various performance criteria that could be considered when developing alternative solutions. Osborne [2] summarized performance criteria from various sources, which would most likely be recognized as authoritative documents. Nonetheless, the following fire risks need to be evaluated in any performance-based fire engineering design.
6.3.2.1 Risk of Ignition

Risk of ignition has traditionally been assessed through the noncombustibility test (CAN/ULC S114) and the surface flame spread test per CAN/ULC S102 [31]. In a building that is prescriptively required to be of noncombustible construction, the allowance for interior finish materials is limited based on their flame spread rating (FSR) or combustibility. Moreover, as a space becomes of greater importance for occupant evacuation, restrictions are imposed on the materials that can be used within this space.

The classification afforded by these two test methods has been proven efficient at reducing fire hazards in buildings. However, given that the results from these test methods are dimensionless, they are somewhat useless to properly understanding the actual fire hazard and/or quantify their contribution to fuel content in terms of potential heat release, smoke production, toxicity of fire effluents, ignitability, etc.

In a performance-based fire design, it is suggested to conduct small-scale tests, such as the ISO 5660 cone calorimeter method [32], to evaluate and quantify the combustion properties of building materials planned to be used in a building. Small-scale test methods are more economical than large-scale tests, and are typically benchmarked to large-scale experiments.

The ignitability of materials can also be evaluated through cone calorimeter tests where a linear correlation between the time to ignition and the irradiance level allows for determining the critical heat flux (CHF) under piloted ignition conditions. Thermal inertia and ignition temperature can also be calculated from the linear correlation. As an example, such material properties are used as input data in the fire growth model implemented into the BRANZFIRE and B-RISK computer fire models [33, 34].

Moreover, several calculation methods have been developed to predict FSR based on cone calorimeter data [35, 36, 37]. While these models have limitations due to the type of tested materials, the fire engineering used to develop them is technically sound and would most likely be appropriate for developing a new categorization system based on cone calorimeter test results, rather than classifying materials based on a dimensionless range of FSR.

In addition to providing fundamental and valuable information for input in computer models, classifying materials based on their heat release rate, and possibly other ignitability parameters, allows for evaluating the effects of burning materials and thus the “risk of ignition”. It is noted that such classification is already implemented in some foreign building codes.

6.3.2.2 Risk of Fire Contribution and Severity

The limitations imposed on the combustibility of building materials aim essentially to limit the risk of contributing to fire growth and severity. In a prescriptive noncombustible construction, it is deemed that a burnout of the fuel content would be achieved due to the limited amount of combustible materials allowed as either interior finish materials (as well as their maximum thickness) or interior wood-framed partitions, among others. As such, a performance-based fire design should include the potential for fire contribution of combustible materials, either as structural elements or interior finish materials, to the fire growth, fully-developed (ventilation- or fuel-controlled) and decay phases. Figure 9 illustrates the different development phases of a fire, quantified in terms of heat release rate. A number of fire growth models were presented by Osborne [2] to predict design fire curves, such as the parametric fires, time-equivalent equations and $t^{2}$ fires.
A greater amount of exposed combustible materials in a fire compartment may reduce the fire growth phase and will increase the duration of the fully-developed phase, depending on various parameters such as the ventilation conditions (i.e. amount of oxygen available to sustain combustion). It would most likely not influence the maximum heat release rate and/or temperature within a compartment as the fire will transition to a ventilation-controlled regime due to the limited amount of oxygen available. In a performance-based design, the impact of a prolonged burning duration will then be captured through an actual fire-resistance assessment, rather than through a standardized fire-resistance rating based on the results of a CAN/ULC S101 test [11].

In a recent paper detailing some of the challenges for designing tall timber buildings for fire safety, Buchanan [38] suggested possibilities for passive fire protection based on the presence of an automatic sprinkler system as well as the height of a building. According to his categorization, shown in Table 4, a building above 9-storeys in height should allow for full burn-out of the fuel content from using a full encapsulation of the mass timber construction. Full encapsulation would also limit the risk that the structural elements ignite, char and contribute to the intensity, severity and duration of a fire. Thus, once the fuel content is consumed, the fire will decay and extinguish without further external interventions (e.g. fire fighters).

<table>
<thead>
<tr>
<th>Building Height Number of Storeys</th>
<th>Low-Rise 1-2</th>
<th>Mid-Rise 3-5</th>
<th>Tall 6-8</th>
<th>Very Tall 9-15</th>
<th>High-Rise &gt; 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evacuation</td>
<td>Quick</td>
<td>Slow</td>
<td>Assisted</td>
<td>Assisted</td>
<td>Difficult</td>
</tr>
<tr>
<td>No Sprinklers</td>
<td>Local areas exposed</td>
<td>No exposed wood</td>
<td>Not allowed</td>
<td>Not allowed</td>
<td>Not allowed</td>
</tr>
<tr>
<td>Normal Sprinklers</td>
<td>Large areas exposed</td>
<td>Local areas exposed</td>
<td>No exposed wood</td>
<td>Full encapsulation</td>
<td>Full encapsulation</td>
</tr>
<tr>
<td>“Special” Sprinklers (1)</td>
<td>Large areas exposed</td>
<td>Large areas exposed</td>
<td>Local areas exposed</td>
<td>No exposed wood</td>
<td>Full encapsulation</td>
</tr>
</tbody>
</table>

(1) Refers to a sprinkler system designed beyond minimum requirements and/or with special features to enhance its effectiveness and reliability.
One can easily reformat Table 4 using different heights per building categories (e.g. Mid-Rise = 3-4 storeys, Tall = 5-6, Very tall = 7-12 and High-Rise ≥ 12) along with current sprinkler protection requirements associated with these heights, and reassign accordingly an appropriate level of passive fire protection.

With the increasing demand for exposed timber in tall buildings, Barber [39] developed two methodologies for assessing the amount of exposed timber in any compartment, whether it is exposed mass timber walls and/or floors (ceilings). The first method is based on the expected total moveable fire load and the additional fuel load due to the combustion of exposed mass timber surfaces. The amount of energy released from the calculated design fire of a given scenario should be less than that of a standard fire-resistance test. The additional fuel load is considered to ignite and contribute when it is exposed to a heat flux greater than 12 kW·m⁻² (assuming that this value corresponds to the mass timber CHF for piloted ignition), and stops contributing when the impinging heat flux is below 5 kW·m⁻². The resulting average charring rate, which is based on the heat flux at which the surfaces are being exposed, is then used to determine the mass of timber that charred and contributed to fire. Assuming a heat of combustion of 18 MJ·kg⁻¹ for timber, the burned mass is then converted into a surface fire load (in MJ·m⁻² of fire compartment) that is added to the initial moveable fuel load. This first method is an iterative process until the resulting total fire load converges within a 5% difference between iterations. The second method consists of an advanced computer modeling using computational fluid dynamics (CFD). It was reported by the author that the first method predicts the fire duration within 20 to 30% of actual test results conducted at Carleton University [40], while the second method provided results within 15% accuracy. It is noted that the challenge in such evaluation methods is to identify the point at which heat delamination of adhesives may occur and result in additional fuel contribution to fire, as observed in full-scale compartment fire tests with CLT elements [40, 41].

Lastly, in the eventuality where automatic sprinklers are installed in tall buildings, the design fire curve can be adjusted accordingly based on the effect of the sprinklers on the fire development. In a worst case scenario, the sprinkler system fails to activate and the design fire will continue growing until it reaches its maximum heat release rate, as shown in Figure 9. If the sprinkler system does activate, it can either control the fire by limiting its heat release rate to a constant value until extinguishment, or it can extinguish the fire. The time of activation of the sprinklers will define the level of heat release rate of the sprinkler-controlled fire (Figure 10). In a performance-based fire design, a given fire scenario where sprinklers activate may sufficiently limit heat flux to exposed timber surfaces, which may prevent their ignition and contribution to the fire severity.

![Figure 10 – Possible effects of sprinklers, as presented in IFEG [21]](image-url)
Quantifying the effects of the contribution of combustible elements on the development of a fire allows for evaluating the “risk of fire contribution and severity”.

6.3.2.3 Risk of Fire Spread Beyond Point of Origin

The concept of compartmentation is already implied within the prescriptive solutions of the NBCC by stipulating minimum fire-resistance ratings of building elements. The NBCC defines a compartment as “an enclosed space in a building that is separated from all other parts of the building by enclosing construction providing a fire separation having a required fire-resistance rating”.

The concept of “fire-resistance” is a performance-based concept and aims at providing a level of performance to structural and separating building elements, regardless of their “combustibility”. As such, fire-resistance ratings of building elements allows for some amount of compartmentation within a floor level, which is not explicitly accounted for in the prescriptive provisions found in Division B. The latter imposes a floor area limit rather than a maximum compartment size per floor.

While NFPA 5000 suggests at least 8 design scenarios be evaluated (refer to Subsection 6.3.1 of this report), additional design fire scenarios should focus on the outcome occurring within the compartment of fire origin, of which the severity of the fire will challenge the compartment boundaries and load-bearing elements.

As mentioned previously, it is deemed that a prescriptive noncombustible construction would achieve a burnout of the fuel content. According to CSA S408 “Guidelines for the Development of Limit States Design Standards” [42], the fire-resistance of a tall building, as determined from Subsection 3.2.6 of Division B of the NBCC, should withstand complete burn-out of the fuel content of any fire compartment. This requirement is somewhat similar to Buchanan’s philosophy [38], as shown in Table 4, for 9-storey buildings and above of which full encapsulation is suggested.

NFPA 557 “Standard for Determination of Fire Loads for Use in Structural Fire Protection Design” [43] provides a risk framework methodology for determining the fire load and fire load density to be used as the basis for the evaluation and design of the structural fire performance of buildings. The standard provides guidance to determine the fire load based on a combination of either: 1) statistical distribution, 2) fire initiation frequency or 3) effectiveness and reliability of the fire protection features that contribute to fire control in the early stages of a fire. As an example, according to NFPA 557, the frequency of fires is to be taken as 6 fires per million square meters per year for office and business occupancies. To that frequency, other modification factors are to be considered based on the type of construction and the presence, or absence, of detection and alarm systems as well as automatic sprinklers. Fire loads should be calculated as both localized fire loads and distributed fire loads, which will result in different fire design scenarios, fire growth and impacts on the building design.

Quantifying the effects of fire on the boundary elements of a compartment allows for evaluating the “risk of fire spread beyond point of origin”.

6.3.2.4 Risk of Structural Collapse

Similarly to the “Risk of fire spread beyond point of origin” described previously, design fire scenarios should evaluate the resistance of load-bearing elements subjected to the thermal effects resulting from these fires.
ISO/TS 24679-1 “Fire Safety Engineering - Performance of Structures in Fire” [29] provides a methodology for applying an engineering approach to the assessment of fire performance of structures in real fires. An evaluation of the thermal response of the structure is to be made, in conjunction with an analysis of the development and heat generated from selected fire design scenarios. An evaluation of the mechanical response is also made as building materials tend to degrade when exposed to elevated temperatures such as those in fire conditions. Typically, the thermo-mechanical assessment is to be made simultaneously. While timber does not exhibit significant thermal elongation/contraction when exposed to fire, other materials do. Thermal elongation/contraction of structural materials exposed to fire may induce internal forces not initially accounted for in the structural design for ambient conditions (i.e. normal use of the building). As such, the interaction between structural elements and frames need to be evaluated as, for example, one beam exhibiting thermal elongation may push the top of a column to a point where structural failure of the column will occur.

Paragraph A-25 of the “User’s Guide – NBC 2010 Structural Commentaries (Part 4 of Division B)” [10] provides a load combination for a rare/accidental event such as a fire, as per the equation below.

\[ 1.0D + T_s + (\alpha L + 0.25S) \]

where \( D \) is the permanent load, \( T_s \) is taken as 0 for statically determinate structures, \( \alpha \) is taken as 1.0 for storage areas, equipment areas, and service rooms, or 0.5 for other occupancies, \( L \) is the live load due to occupancy and \( S \) is the snow load.

Lastly, while post-earthquake fires can occur, it is noted that fires and earthquakes are both considered to be rare events and thus not expected to occur at the same time. Therefore, horizontal actions due to wind and seismic forces are typically not considered for structural fire-resistance, unless specifically stipulated in the applicable building code.

Quantifying the effects of fire on the load-bearing elements of a compartment and/or building evaluates the “risk of structural collapse”.

6.3.2.5 Risk of Fire Spread to Neighbouring Buildings

Another risk to be evaluated is the potential for a fire to spread to neighbouring buildings. A prescriptive solution would stipulate minimum spatial separation between buildings and/or property lines based on a percentage of unprotected openings (e.g. windows). The spatial separations are based on simple equations to predict the emitted heat flux from a fire source to a receiving surface. The amount of energy implied in Division B of the NBCC is based on real-scale experiments called the “St-Lawrence Burns”, conducted back in the 1950s [44]. The NBCC limiting performance criteria is that the receiving surface (i.e. neighbouring buildings) should not be exposed to an irradiance level greater than 12.5 kW·m\(^{-2}\), which is the typical CHF for piloted ignition of most softwoods.

In a performance-based design, the actual emitted radiation from a fully-developed fire would be calculated using the same equations, such as those given in Eurocode 1: Part 1-2 “Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire” [45], and would be compared to the CHF value of the materials installed on the exterior facades of neighbouring buildings. As mentioned previously, the CHF of a material can be evaluated from a series of cone calorimeter tests at various heat flux levels. Otherwise, the traditional value of 12.5 kW·m\(^{-2}\) for wood material can be used as the performance criteria.
A fire that may spread along the surface of a building may also pose a threat to adjacent buildings. As such, the potential for upward fire spread along a façade also need to be assessed. Methods to reduce exterior flame spread include the use of low-combustibility materials in exterior walls, eliminating cavities, exterior sprinklers and/or some specific design configuration of the exterior façade that would provide “barriers” to limit fire from spreading outside.

Quantifying the energy from a fully-developed fire impinging on neighbouring buildings and the propensity of fire to spread upward along an external façade evaluates the “risk of fire spread to neighbouring buildings”.

### 6.3.2.6 Risk to Safety of Occupants

In fire design, ensuring occupant safety is typically the primary goal. In a performance-based design, the ability of occupants to escape safely is paramount and should consider the number of and mobility of the occupants expected to be present in the building. The location of occupants within a building, at any time, and their displacement changes over time during normal use. How occupants move during emergency events depend on the interaction of a variety of parameters related to the characteristics of the building and the occupants, the fire development as well as the fire safety management system proposed for the building.

Two important attributes that need to be accounted for are the available safe escape time (ASET), and the required safe escape time (RSET). ISO 13943 “Glossary of Fire Terms and Definitions” [46] defines the ASET as “the calculated time interval between the time of ignition and the time at which conditions become untenable such that the occupant is unable to take effective action to escape to a place of safe refuge”. In a performance-based design, each occupant may have a different ASET, depending on their personal characteristics such as physical and cognitive abilities that affect their decision-making and behavioural processes (e.g. recognition, response and travel speed). Per ISO 13943, the RSET is “the calculated time for the occupant to travel from his location at the time of ignition to a place of safe refuge” [46]. In a successful evacuation scenario, the ASET needs to be greater than the RSET, ideally with a margin of safety, typically determined by the fire engineer.

Tenable conditions should also be predicted through a performance-based design as they will directly impact the ASET. Tenable conditions include the thermal effects on humans, toxicity of fire effluents (which could lead to incapacitation), smoke and hot layer height as well as visibility. Several performance criteria related to safety of occupants can be found in Hadjisophocleous et al. [30], in a Nordic Technical Specification INSTA TS 950 [47] and in ISO DTR 16756 “Fire safety engineering — Examples of fire safety objectives, functional requirements and safety criteria” [48]. Table 5 summarizes some of the performance criteria given in ISO DTR 16756, as per fire engineering regulations in France and New Zealand.

When using a performance-based design approach (such as fire modeling), it can be demonstrated that some code-compliant design solutions may exhibit relatively unsafe characteristics with respect to occupant evacuation [49]. As such, rather than prescribing maximum travel distance within a floor, quantifying the ASET, the RSET and other safety parameters allows for a better evaluation of the “risk to safety of occupants”. It is noted that current prescriptive provisions of the NBCC seem lacking with respect to addressing fire safety of occupants [2] and these issues need to be quantified against explicit performance criteria.
Table 5 – Tenable conditions for occupants, as per ISO DTR 16756 [48]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Maximum gas temperature of 60°C.</td>
</tr>
<tr>
<td>Thermal</td>
<td>Maximum incident heat flux of 2.5 kW·m⁻² (for an exposure time ≤ 10 s). Maximum incident heat flux of 2.0 kW·m⁻² (for an exposure time &gt; 10 s). Maximum radiative dose of 300 kW⁴/₃·m⁻⁸/₃·s.</td>
</tr>
<tr>
<td>Visibility</td>
<td>Minimum visibility of 10 m (rooms &gt; 100 m²). Minimum visibility of 5 m (rooms ≤ 100 m²).</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Maximum fractional effective dose of thermal effects (FED) of 0.3. Maximum fractional effective dose of CO (FED) of 0.3.</td>
</tr>
</tbody>
</table>

6.3.2.7 Risk to Safety of Fire Fighters

Safety of fire fighters and other emergency responders are typically implied in the intent statements of the NBCC, and thus typically accepted. As an example, the intent statement requiring a building to be of noncombustible construction reads as follows: “To limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm persons” [25]. However, as with provisions to address safety of occupants, the performance criteria are not well-defined, quantified or documented. A performance-based fire design should explicitly quantify the level of safety of fire fighters.

Moreover, CSA S408 [42] stipulates that structures should be designed with adequate load-bearing capacity and with the capability to maintain structural integrity for a sufficient time to a) permit evacuation of the occupants, b) provide appropriate protection for firefighting services and c) protect the building and adjoining property from the spread of fire. Therefore, the load-bearing and separating functions of building elements exposed to fire need to provide enough duration for fire fighters to perform their duties, as evaluated per Subsections 6.3.2.3 and 6.3.2.4 of this report.

As examples, fire engineering regulations from France and New Zealand, as summarized in ISO DTR 16756, suggest that fire fighters shall not be exposed to an incident heat flux greater than 5 kW·m⁻² as well as to a maximum quantity and temperature of smoke during their intervention.

As such, ensuring enough fire-resistance to building elements and quantifying the thermal effects impinging on fire fighters during their intervention allow for a better evaluation of the “risk to safety of fire fighters”.

6.4 Seismic Engineering Design

Due to its complexity of design and the severity of damage after a severe earthquake, seismic design has always been on the forefront of developing performance-based design criteria. The design and construction of wood buildings in Canada is regulated at the provincial level and enforced at the local level, using provincial codes that are based on the NBCC and CSA O86. Building owners and occupants generally believe that if the building satisfies the code provisions for safety, only minor damage of the building is anticipated during a seismic event. Property and insured losses during
earthquakes led to awareness that the level of structural and non-structural damage that could occur in code-compliant (prescriptive) buildings may not be consistent with public notions of acceptable performance. Experiences from earthquakes at the end of the 20th century (e.g., Northridge 1994 and Kobe 1995), as well as those in the 21st century (Christchurch earthquakes of 2011), have forced recognition that severe damage may occur in buildings designed in accordance with the NBCC. Furthermore, recognition that code-based strength and ductility requirements applicable to the seismic design of new buildings are not always suitable for the evaluation. Updating existing buildings has led to the development of performance-based engineering methods for seismic design.

### 6.4.1 Design Process

The performance-based seismic design (PBSD) process explicitly evaluates how a building is likely to perform given the potential seismic hazard it is likely to experience. It also considers uncertainties inherent in the quantification of the potential hazard and the uncertainties in the assessment of the actual building response. In PBSD, identifying and assessing the performance capability of a building is an integral part of the design process that guides numerous design decisions.

In a PBSD process for tall and large wood buildings, design professionals, owners, and other stakeholders jointly identify the desired building performance criteria at the outset of a project. As design decisions are made, the effects of these decisions are evaluated to verify that the final building design is capable of achieving the desired performance. Figure 11 shows a flowchart that presents the key steps in the PBSD process of tall and large wood buildings. Identical to a performance-based fire design, it is essentially an iterative process that begins with the selection of performance objectives, followed by the performance of a preliminary design, an assessment as to whether or not the design meets the performance objectives, and lastly revises design and/or objectives, and reassessment, if required, until the desired performance level is achieved.

![Figure 11 – Simplified diagram for performance-based seismic design](image)

PBSD of tall and large wood buildings begins with selection of one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring damage or loss for identified earthquake hazards. Decision-makers including owners, developers, design professionals,
and building officials will typically participate in the selection of performance objectives. This process may consider the needs and desires of a wider group of stakeholders, including prospective tenants, lenders, insurers, and the general public. The needs and opinions of others can have an indirect impact on the design of a building, but these groups generally do not have an opportunity to directly participate in the design process.

Once performance objectives are selected, designs must be developed and the performance capability determined. As a minimum, basic building design information includes: (1) the location and characteristics of the site; (2) building size, configuration, and occupancy; (3) structural system type, configuration, strength, and stiffness; and (4) type, location, and character of finishes and nonstructural systems. For new buildings, preliminary design information must be developed to a sufficient level of detail to determine performance capability. In the case of existing buildings, basic building design information is already defined, but preliminary retrofit measures must be developed.

Performance assessment is the process used to determine the performance capability of a given building design. In performance assessment, engineers conduct structural analyses to predict building response to earthquake hazards, assess the likely amount of damage, and determine the probable consequences of that damage.

Following performance assessment, engineers compare the predicted performance capability with the desired performance objectives. If the assessed performance is equal to or better than the stated performance objectives, the design is adequate. If the assessed performance does not meet the performance objectives, the design must be revised or the performance objectives altered, in an iterative process, until the assessed performance and the desired objectives match.

6.4.2 Performance Criteria and Seismic Performance Assessments

The first-generation PBSD documents, e.g. FEMA 273, FEMA 274, the NEHRP Guidelines for the Seismic Rehabilitation of Buildings [50] and its companion document, the NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings [51], and Vision 2000: PBSD of buildings [52], outlined the initial concepts of performance criteria related to damageability and varying levels of hazard. A building performance level is obtained by combining a structural performance level (Life Safety and Collapse Prevention) with a non-structural performance level (Immediate Occupancy). Second generation documents, which include FEMA 356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings [53] and the American Society of Civil Engineers (ASCE) Standard ASCE/SEI 41-06, Seismic Rehabilitation of Existing Buildings [54], define the current practice for PBSD in the U.S. In ASCE 41-06, the building performance is expressed in four discrete Structural Performance Levels (SPL) and two intermediate Structural Performance Ranges. The discrete SPL are Immediate Occupancy (S1), Life Safety (S3), Collapse Prevention (S5) and Not Considered (S6). The intermediate Structural Performance Ranges are the Damage Control Range (S2) and Limited Safety Range (S4). Although they established a vocabulary and provided a means by which engineers could quantify and communicate seismic performance to clients and other stakeholders, implementation of present-generation procedures in practice uncovered certain limitations and identified enhancements that were needed.

The PBSD procedures are constantly improving. FEMA initiated a series of projects that are referred to as the ATC-58 Projects, to further improve the latest procedures. The first step was publishing the FEMA 445, Next-Generation PBSD Guidelines for New and Existing Buildings [55], and the final FEMA P-58 Performance Assessment of Buildings [56, 57]. Also, an updated version of the ASCE 41-13 standard [58] is available. The methodology specified in FEMA P-58 expresses performance in the form of probable impacts, in terms of casualties, repair costs, repair time, and unsafe placarding, considering inherent uncertainties. Unlike earlier versions of PBSD, the FEMA P-58 methodology

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utilizes performance measures that can be understood by decision makers. Performance objectives relate to the amount of damage the building may experience and the consequences of this damage including potential casualties, loss of use or occupancy, and repair and reconstruction costs. They can also be used to assess potential environmental impacts, including generation of waste, expenditure of energy, or creation of greenhouse gases.

The Pacific Earthquake Engineering Research (PEER) Center developed guidelines [59] for performance-based seismic design of tall buildings considering the seismic response characteristics of tall buildings, including relatively long fundamental vibration period, significant mass participation and lateral response in higher modes of vibration, and a relatively slender profile. Properly executed, the guidelines are intended to result in buildings that are capable of achieving the seismic performance objectives for Occupancy Category II buildings intended by ASCE 7. Alternatively, individual users may adapt and modify these guidelines to serve as the basis for designs intended to achieve higher seismic performance objectives.

Three types of performance assessments are provided by FEMA P-58. They include intensity-based, scenario-based, and time-based assessments. Intensity-based assessments evaluate the probable performance of a building assuming that it is subjected to a specified earthquake shaking intensity. Shaking intensity is defined by 5% damped, elastic, acceleration response spectra. This type of assessment can be used to assess the performance of a building for design earthquake shaking consistent with a building code response spectrum, or to assess performance for shaking intensity represented by any other response spectrum. Scenario-based assessments evaluate the probable performance of a building assuming that it is subjected to an earthquake scenario consisting of a specific magnitude earthquake occurring at a specific location relative to the building site. Scenario assessments are useful for buildings located close to one or more known active faults. This type of assessment can be used to assess the performance of a building in the event that an historic earthquake is repeated, or a future projected earthquake occurs. Scenario-based assessments are similar to intensity-based assessments except that they consider uncertainty in the intensity of earthquake shaking, given that the scenario occurs. Time-based assessments evaluate the probable performance of a building over a specified period of time (e.g., 1 year, 30 years, or 50 years) considering all earthquakes that could occur in that time period, and the probability of occurrence associated with each earthquake. Time-based assessments consider uncertainty in the magnitude and location of future earthquakes as well as the intensity of motion resulting from these earthquakes. The time period for time-based assessment depends on the interests and needs of the decision-maker. Assessments based on a single year are useful for cost-benefit evaluations used to decide between alternative performance criteria. Assessments over longer periods of time are useful for other decision-making purposes.
7 ADVANCED COMPUTER MODELS

As mentioned previously in this report, the use of advanced computer modeling will most likely be required given the complexity of a performance-based design. This section provides additional information related to commercial software packages and the types of analysis that can be done.

7.1 Fire Modeling

Subsection 0 is a summary of a previously completed review of current computer models, completed by Dagenais & Peng [49]. Fire modeling is widely used in performance-based fire design when developing and supporting an innovative design that does not follow the prescriptive solutions.

7.1.1 Fire Dynamics

As reported by Pope & Bailey [60], advances in fire science and engineering have allowed for rapid progression in fire and smoke modeling. As such, the traditional prescriptive design is no longer the only compliance method for designing a fire-safe building. Parametric modeling, zone models and field models using computational fluid dynamics (CFD) are among the most commonly used in the fire engineering community.

Models such as simple analytical models, also called “parametric fire curves”, may be useful to conduct a preliminary analysis. Being easy to use, these models can be run quickly and usually require limited input for their use. However, the applicability of their results may also be limited. Eurocode 1: Part 1-2 [45] is one of the most commonly used parametric models to rapidly determine the heat release rate, temperature of the hot layer, and thermal effects from a localized fire.

A fire zone model is the most commonly used numerical fire model and is typically used as a standalone computer program or in a spreadsheet. They are essentially one-dimensional and divide the fire compartment (volume) into two distinct zones: 1) a hot upper layer created by the fire plume and 2) a cold lower layer. Such zone models, also called “two-zone models”, can determine the upper and lower layer temperatures and heights, the fire plume mass flow rate, the flow rate through openings (doors and windows), the heat release rate, and the rate of combustion.

A more advanced method to predict fire growth, smoke transport, toxicity and heat transfer, among other parameters, is the use of field models that use computational fluid dynamics (CFD). Such models divide a given space into numerous control volumes where mass, momentum and energy conservation are numerically solved for each volume. Fire Dynamics Simulator (FDS), developed by NIST, has extensively been used in the fire engineering community.

CFD modules in commercially available finite element software may also be used to couple transient thermal and structural analysis. Typically, transient thermal-structural finite element models are “1-way” coupling, meaning that the thermal analysis is being performed and results are then sent to the structural model afterwards, independent of each other.

7.1.2 Occupant Evacuation Modeling

Several computer models have been developed over the years for assessing occupant evacuation. The following are some of the most commonly used evacuation models, as summarized in [49].
Evacuation is typically complex and it is difficult to properly evaluate its time. However, simple models are available and detailed in Sections 3-11 to 3-17 of the SFPE Handbook of Fire Protection Engineering [61]. These models provide information to calculate the ASET, which needs to be greater than the RSET, as detailed in Subsection 6.3.2.6 of this report.

The “hydraulic model” is a simple model which can be used to quantify the egress performance of a design and, most importantly, enables comparison between different variants to be made [62]. It assumes that the egress paths are continuously used at their maximum capacity from the moment of alarm detection to total evacuation of occupants and thereby does not account for human decisions (or indecisiveness) during emergency conditions and other changing factors such as smoke density, blocked egress, etc. According to this simple model, the RSET can be divided into distinct time intervals as per the following equation.

\[ RSET = t_d + t_n + t_{p-e} + t_e \]

Where \( t_d \) is the time from fire ignition to detection, \( t_n \) is the time from detection to notification of occupants of a fire emergency, \( t_{p-e} \) is the time from notification until evacuation starts (pre-evacuation phase) and \( t_e \) is the time from the start of evacuation until safety is reached (evacuation phase). The hydraulic model of human flow relates to the effective width (usable width) of components, population density, speed, flow characteristics, time for passage through a component and transitions between components. Gwynne & Rosenbaum [62] provide the details for the hydraulic model, such as the relationship between the population density and speed and the maximum exit flow speeds, and also provides calculation examples.

Agent-based egress and human movement simulators are more advanced and sophisticated. They essentially consist of a combined agent-based egress calculation model and a CFD model of fire-driven fluid flow, where the fire and egress parts are interacting. The models compute the position, the velocity, and the dose of toxic gases (CO, CO\(_2\) and O\(_2\)) of each occupant inside the computational domain at each discrete time step.

### 7.2 Seismic Response Analysis and Modeling

#### 7.2.1 Analyses for Performance Assessment

Four levels of analysis are provided in ASCE 41-13, which give designers progressively detailed information about structural performance. The first two levels match the model code style of force-based design and cannot be used on buildings with long periods or significant irregularities. The second two are based on displacement demand and able to directly determine the post-yield capability of the buildings. In addition to a set of general analysis requirements each analysis method is defined in terms of specific modeling requirements and procedures. A common acceptance criterion is provided for linear methods (force-based) and also for nonlinear methods (displacement-based). The criteria are extensive, organized by material type, and based on the amount of available information, including applicable test results.

The first level of analysis is Linear Static Procedure (LSP), which provides an equivalent lateral force, vertical distribution of forces and rules for modeling as well as acceptance criteria. This procedure is similar to the equivalent lateral force procedure in the NBCC, except that the base shear is much higher and the ductility factors are much smaller. It is intended to be simple and very conservative in order to allow one- and two-storey buildings of regular configuration to pass, because of their excessive strength. This may be suitable for low but large wood buildings. The second level of
analysis is Linear Dynamic Procedure (LDP), which uses modal analysis and site-specific response spectra to determine force demands. The LDP also includes modeling rules that prompt consideration of soil structure interaction and appropriate acceptance criteria. It is much more beneficial than the LSP analysis, as it uses site-specific response spectra, calculated building periods, and the beneficial effects of multiple modes. It does have a serious limitation: it cannot properly evaluate a building that retains significant strength after damage begins to occur, which is characteristic of a building with significant redundancy. The rules for judging the building to be adequate trigger unacceptable performance when the first significant element within the stiffest lateral system exceeds its limits. For some buildings, this technique is satisfactory; once significant yielding occurs, there is nothing else to provide resistance.

The first of the displacement-based procedures is Nonlinear Static Procedure (NSP). Using analytical techniques, accessible in commercially available advanced computer programs, a model of the building is subjected to increasing deflection, while the impact on the lateral force resisting elements is monitored. As the yield limits are exceeded, the elements are allowed to yield and the computer program tracks their post yield displacement to determine when the building loses its lateral force resisting ability. In the process, first significant yield does not signal a problem; instead, it signifies that other elements need to step up and take over. Using a series of approximations, analysts calculate a target displacement, based on site-specific response spectra. If there is a lateral system within the building that can keep the movement to within the target displacement, the building is judged adequate. If not, then there is one more level of analysis, if the building warrants the cost of running it. This process of analysis matches the way buildings behave in earthquakes, since it estimates the building’s actual movement and resulting damage.

The second displacement-based method is Nonlinear Dynamic Time History Procedure (NDTHP) that uses ground motion records to represent the possible shaking that the site could experience. The frequency content of the records is used directly to determine the displacement demand and gives a more accurate representation. In addition, the number of cycles of nonlinear behaviour can be monitored and used to more accurately predict the extent of damage that will result from the nonlinear behaviour. Buildings that need to rely on a high level of nonlinear behaviour to achieve their target displacement benefit most from the NDTHP. Buildings that are heavily damaged in earthquakes, but remain standing straight up, illustrate the beneficial effects of time history record. Only NDTHP is capable of predicting such behaviour.

7.2.2 Modeling of Tall and Large Wood Buildings under Earthquake Actions

In general, a three-dimensional (3D) numerical model is necessary to study the seismic behaviour of a tall and/or large wood building. There are numerous commercially available software packages that can help engineers to develop linear and nonlinear models of buildings. Examples of general purpose finite elements software for practicing engineers include ETABS, SAP2000, RFEM, RSTAB, Perform 3D, STAAD, RISA, RAM, ABAQUS, ADINA, ANSYS, Structural System, S-Frame, P-Frame, ST STRUDEL, Visual Tools and many others. Software for nonlinear time-history analysis includes OpenSees, SeismoStruct, Nonlin and Nonlin-Pro. Specific software packages for nonlinear analysis of wood-frame structures are also available, e.g. SAPWood [63], SAWS and CASHEW [64]. They assume that the diaphragms in the building are rigid, and all nonlinear action occurs in the wood frame shear walls. In addition to time domain analysis, several modules that support the NEESWood PBSD efforts are also included in SAPWood.

The behaviour of tall and large wood structures under various types of loading is largely controlled by the connections and assemblies they connect. When a general purpose software package is used for modeling taller and larger buildings, wood beam, column, or wall (panel) elements should, in most cases, be modeled as linear elastic beam or shell elements, with their strength and stiffness properties
included for all different directions. The connections or assemblies should be modeled using hysteretic models that will allow for adequate capture of the strength and stiffness degradation, as well as the pinching of the loops that is characteristic of most wood connections and assemblies, see Figure 12. The input parameters needed for the analytical models are discussed in detail below. It should be noted that for general purpose commercial software, one may need to derive the effective stiffness of engineered wood products/panels that are part of the structural system with and without the effect of the connections for carrying out linear static and response spectrum (dynamic modal) analysis.

![Figure 12 – Typical hysteresis behaviour of a timber connection](image)

Some of the important input properties that are needed to develop numerical models of the tall and large wood buildings to perform static and dynamic analyses are listed below:

(a) **Element Properties**

Elements in wood-based buildings will most probably consist of engineered wood products either used as beam/column elements, structural wall panels, or a combination thereof. In hybrid buildings, some steel, concrete or even masonry elements may be present. For analysis and modeling purposes, the effective stiffness of the engineered wood products/panels, with and without the effect of the connections, must be determined in three major directions. Lower bound, upper bound, and best estimates of the strength and stiffness properties should be determined.

(b) **Hysteresis and Backbone Models for Connections and Assemblies**

Nonlinear load-deformation relationships (backbone and hysteresis curves) for the main parts of the lateral load-resisting system (connections and assembles) should be obtained if nonlinear dynamic analyses are conducted. If information from the literature is lacking for a specific geometry and application, tests should be carried out on representative samples (e.g., representative of the
材料的使用，以及制造和装配的公差）由认可的实验室进行测试，以确定适合分析的 hysteretic/backbone 曲线。

(c) 有效阻尼

有效粘性阻尼对钢和混凝土结构通常假定在 2-5%。木结构的阻尼值通常略低，因此，用于包括线性动力响应历史模型中的木结构的主要抗力元素和装配的线性阻尼响应历史模型可能假定在 1-3%的范围内，除非有来自可用实验数据的更高值的充分理由。应指出，耗散阻尼效应将明确包含在非线性动力模型中。不应将粘性阻尼赋给包含摩擦装置的构件。

(d) 土质性质和土-结构相互作用

对于高耸建筑，土质和基础的相互作用可能影响整体性能，因此，土-结构相互作用在开发线性或非线性动力分析时应相应地建模。通常，土质性质用一系列水平和垂直弹簧或土质元素来模拟。已建立的程序用于确定弹簧和元素的性质。岩土工程师应提供合适的土质弹簧或元素的性质，以便为指定的基座和土质条件提供合适的弹簧或元素。对于上、下限应使用不同的弹簧或元素性质，以限制建筑物的力和位移需求。

(e) 输入地震运动

输入地震运动应由岩土工程师为指定地点提供，使用该区域的地震活动性和土质剖面。值得注意的是，土木工程系在不列颠哥伦比亚大学已开发了一套输入地震记录，适用于各种地震场景和土质条件。此外，NRCC 将在即将发布的 2015 年结构评论中发布建立特定时间历史的推荐程序，以及一些推荐的时间历史记录，适用于各种地点。这些模型的有效性至关重要，特别是在创新装配和后果严重的建模时。用于模型的计算模型或模型的组件、连接和装配的静力/动力模型必须与可用的测试结果数据验证，以确保等效性质和模型假设在静力/动力模型中产生合理结果。这些简化和验证的模型可能需要进一步发展以开发出更复杂、更可靠的木结构。例如，静力分析的结果，如柱或墙的永久荷载和永久和活荷载，应与手拉计算进行比较。高耸和大木结构的基频应与可用的实验公式和任何可用的相似测试数据进行比较，以确保结果不包偏。

The model validation is essential, especially for innovative assemblies and where the consequences for inappropriate modeling are serious. The analytical models or analogues used to model the components, connections, and assemblies of tall and large wood buildings have to be verified against the available test result data, to ensure that equivalent properties and model assumptions used in the static/dynamic model produce reasonable results. These simplified and verified models may then be extrapolated to develop more complex, robust models of wood buildings. Also, it is suggested that the results from the developed numerical model of the building (static and dynamic analyses) be checked against simplified methods of calculation. For example, the results of the analytical model, such as column or wall gravity load takedown, should be compared with hand calculations for calculating column and wall loads under dead and live loads. The fundamental periods of tall and large wood buildings computed by modal analysis should be compared with available empirical formulas and any available similar test data to ensure the results are not biased.
7.3 Guidance on Use of Computer Models

Guidance on the appropriate use of computer models for tall and large wood buildings is provided below, based on Appendix E of the ICCPC.

NFPA 5000 further stipulates that the performance assessment of a performance-based design shall be made through the use of appropriate calculation methods. The latter shall be approved by the AHJ, which further supports the need that AHJs be involved from the beginning of a performance-based design as ultimately, they will be responsible for its approval. Additional information related to input data and safety factors can be found in Section 5.6 of NFPA 5000. Calculation methods should be well-documented (namely their scope of application, assumptions and limitations), validated, suitable for the intended task and most importantly generate outputs that can be compared with the agreed upon performance criteria [21].

Lastly, a recent guide on fire modeling has also been published jointly by FPInnovations and the BC Advisory Group on Advanced Wood Design Solutions [65]. The guide provides a methodology to assess the fire performance of exterior wall assemblies incorporating combustible components using small-scale testing and CFD models as an alternative approach to conducting a full-scale standard fire test. Guidance on model calibration, documentation and analyses is also given.

7.3.1 Requirements

All computer modeling work is required to be conducted under the guidance of the design professional. Although jurisdictions may not require licensing or certification for a computer model operator (e.g., structural, fire, mechanical, energy), knowledge and experience are needed in the application of the program limits and the performance-based design objectives for compliance with performance-based code objectives.

Computer program data shall also be submitted as part of documentation (e.g., program name, brief description, type of analysis and application, program input and output units and description, and how it is to be used to support design). Statements of exact mathematical model(s) and accompanying sub-model(s), if any, uncertainty, assumptions, limitations, scope of applicability and a few reproducible simple benchmark cases shall be included.

Moreover, background data must be submitted to substantiate why particular scenarios are rejected or accepted.

7.3.2 Responsibility and Limitations

The computer modeling approach is merely a tool for high-speed calculations that provides mathematics calculations, graphical and related results. It is the design professional's responsibility to incorporate the above data and background information required as documentation for his or her design document submittal.

Lastly, it is noted that all models, simple or sophisticated, have limitations and it is the responsibility of the designers to know their limitations and apply them suitably based on their engineering judgment.
8 CONCLUSION AND RECOMMENDATIONS

With the shift in design philosophy first introduced in the 2005 NBCC, compliance to the NBCC can now be achieved by either complying with the prescriptive provisions given in Division B or by using “alternative solutions” that must achieve at least the minimum level of performance required in Division B in the areas defined by the objectives and functional statements attributed to the applicable acceptable solution it is replacing. Previous reports by FPInnovations aimed at understanding how performance-based building codes around the world address fire safety, investigating and identifying gaps in current knowledge with respect to performance criteria for wood-based building systems as well as developing performance criteria for wood-based design systems meeting the objectives and functional requirements set forth in the NBCC.

The objectives of the current project were to develop a performance-based design process for wood-based design systems meeting the objectives and functional statements set forth in the NBCC, and to provide guidance for compliance of innovative wood building systems currently not covered in the Canadian regulatory system, in particular related to fire and structural performance attributes.

A review of current wood building systems identified that the combustibility of these materials drastically limits their range of applications as they are cornered into the “combustible construction” classification, along with the implied fire risk hazard and limitations associated with this category.

In this report, a performance-based design process is provided for wood-based design systems meeting the objectives and functional statements set forth in Division A of the NBCC. The proposed approach focuses on the actual performance level of a given solution (i.e. identify and quantify the level of acceptable damage/risk during and after a major event) as opposed to using prescribed design solutions intended to achieve a certain (and undefined/implicit) performance level. Quantifying the relevant risks and/or levels of tolerated damage allows for a better evaluation of a building design, while neglecting the categorization of “combustible construction”.

Guidance on quantifying performance groups, tolerated damage levels and relevant risks were presented. Several authoritative documents and standards from foreign countries have been detailed and identified as suitable documents to support the evaluation of a performance-based design in Canada.

Lastly, it is imperative that the NBCC does not explicitly require that an alternative solution needs to demonstrate a level of performance at least equivalent to prescriptive acceptable solutions (i.e. a comparative approach). The latter are deemed-to-provide the required level of safety and are mostly evaluated qualitatively through a technical consensus of different stakeholders and building experts, and thus difficult/impossible to quantify.

Every building is unique and distinct (although there can be significant similarities) and its design and evaluation will thereby be unique and distinct. As such, depending on the design objectives, an alternative solution may still fulfill the objectives and required performance criteria based on engineering analyses, which were agreed upon as suitable, reasonable and reliable to ensure a safe and satisfactory design (i.e. an absolute approach). It is noted that in the US, the ICCPC does not require that a performance-based design needs to demonstrate at least the same level of performance to that attributed to the prescriptive solutions found in the International Building Code.
9 REFERENCES


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