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White Paper on Fire Resistance of Timber Structures

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Prepared for
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Notice

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WHITE PAPER

FIRE RESISTANCE OF TIMBER STRUCTURES

A report for the National Institute of Standards and Technology

by

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Final report

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1 Introduction

Timber structures have experienced a renaissance during the recent few decades due to their environmental credentials, and societal goals striving for sustainable development with lower energy demands and less pollution in all sectors including the construction sector that stands for a major part of the overall community economy.

However, the combustibility of timber still limits its use as a building material by restrictions in building regulations in most countries, especially for higher and larger buildings. Several research projects on the fire behaviour of timber structures have recently been conducted world-wide aimed at providing basic data on the safe use of timber. The results have been relaxations introduced during recent years, especially in Europe.

Overall, the research and basic understanding of timber structures in fire is limited compared to traditional building materials, since large timber structures have been forbidden for a long time. The developed design concepts and models are mostly limited to standard time-temperature exposure (e.g. ISO 834-1 and ASTM E119). The need for further studies of the fire behaviour of timber structures is therefore large, in particular with regard to the global structural behaviour of realistic buildings exposed to natural fires.

1.1 Scope of this Report

Fire resistance of timber structures is a very large field. In order to keep this document relatively small, the scope of is limited as follows:

- This report attempts to define a Performance-Based framework for the fire safety design of multi-story timber buildings.
- The report concentrates on medium-rise multi-story timber buildings from 3 stories to 10 stories tall, which are likely to be most popular and technical feasible. Taller buildings are discussed briefly.
- The report concentrates on "mass timber" buildings, constructed from large timber posts and beams (from LVL or glulam) and large wood panel construction using cross-laminated timber (CLT) or other heavy timber panels. Light wood frame buildings protected with gypsum plasterboard (2 by 4 construction) have been covered elsewhere and are not considered to be feasible for building above about 6 stories.
- The report concentrates on the fire resistance of structural elements and assemblies, and does not include early fire safety issues such as ignition and flame-spread on wood surfaces. It does not address broader fire safety issues such as fire safety systems, fire fighting, or evacuation.
- External fire spread via building facades and windows is partly included, since wooden façade claddings are considered by many architects to be an essential feature of timber buildings, at least up to 8-10 stories.

- Automatic fire sprinkler systems are discussed briefly, since the combination of active and passive fire protection is considered to be an important way to provide fire safety for tall timber buildings.
- Fire resistance of timber connections is included briefly, including both mechanical fasteners and glued connections. The influence of adhesives on the fire behaviour of bonded structural timber elements is discussed briefly.

1.2 Other Recent Reports

There are a number of excellent recent international publications on fire safety in timber buildings. These publications are summarised below.

1.2.1 Technical Guideline for Europe

A comprehensive European report (Östman et al., 2010) describes the work of a multi-national committee which produced *"Fire Safety in Timber Buildings - Technical Guideline for Europe"*. This comprehensive 200 page document gives the background and design methods for designing timber buildings to have similar fire safety to buildings of other materials. The report refers mainly to fulfilling requirements according to the recent European system for fire safety in buildings (CPD), but the basic principles are all applicable in North America and elsewhere.

This excellent report has chapters on fire safety objectives, wood products as linings, flooring and facades, fire stops, service installations and active fire protection. Advanced calculation methods are provided for both separating timber structures and load-bearing timber structures with and without layers of gypsum board protection. Performance-based fire design is discussed with reference to methods of quantitative risk assessment.

1.2.2 Fire Safety Challenges of Tall Wood Buildings

More recently the Fire Protection Research Foundation (Gerard et al., 2013) has produced *"Fire Safety Challenges of Tall Wood Buildings"* which has an extensive literature list and case studies of modern timber buildings around the world.

The report also gives a comprehensive gap analysis, leading to recommendations for future research and testing:

- Fire testing of new and innovative timber and hybrid solutions
- Full-scale / large-scale fire testing of mock up tall timber frames
- Natural fire testing in full-scale / large-scale tall timber frames
- Economic analysis to quantify construction, operation and costs of tall timber buildings
- Emphasis on effective risk communication and education.

1.2.3 Tall Wood Buildings in Canada

FPInnovations (2013) has recently published a 90% draft of the *"Technical Guide for the Design and Construction of Tall Wood Buildings in Canada"*. Chapter 5 (Fire Safety and

Protection) covers much of the same material from a Canadian perspective in 60 pages. Understandably, this report is strongly related to the objective-based National Building Code of Canada (NBCC), with much attention on providing an "alternative design" which meets the minimum fire performance implied by the "acceptable solution" of the prescriptive Division B of the NBCC. Unfortunately this concentration on the NBCC draws attention away from the basic principles of fire safety design.

The report gives recent examples of heavy timber construction in Canada, with useful sections on the fire resistance of penetrations and concealed spaces, façade spread, and flame spread rating of exposed timber surfaces, with a useful summary of risk assessment methods for fire safety.

Section "5.12 Consideration of Major Natural Disasters" describes the need to design some buildings for extreme scenarios where water supplies and emergency services may not be available. Such events have very low probability but potentially high consequences, especially for tall buildings. Design for such disasters requires design for complete burnout including the decay phase of any compartment fire, hence stringent measures such as "complete encapsulation" of the timber structure and provision of an emergency on-site water supply.

To provide fire safety equivalent to non-combustible steel or concrete construction, the report promotes "complete encapsulation" of wood to provide two hours of fire resistance before any charring of the underlying wood occurs. Some situations may be satisfactory with "limited encapsulation" and others with fully exposed timber surfaces, provided that the building code requirements are met. This is discussed in more detail later in this report.

1.2.4 Use of Timber in Tall Multi-Story Buildings

The International Association for Bridge and Structural Engineering (IABSE) has recently published a Structural Engineering Document (SED) on the Use of Timber in Tall Multi-Story Buildings (Smith and Frangi, 2014). The document addresses a reawakening of interest in timber and timber-based products as primary construction materials for relatively tall, multi-story buildings. Emphasis throughout is on the holistic addressing of various issues related to performance-based design of completed systems, reflecting that major gaps in know-how relate to design concepts rather than technical information about timber as a material.

Special consideration is given to structural form and durability aspects for attaining desired building performance over lifespans that can be centuries long. Chapter 3 describes fire safety concepts for tall buildings, based on the scenario that occupants located in upper parts of buildings cannot leave during fires, and fires cannot be extinguished so they may continue until all combustible material in any affected fire compartments has burned. Based on this scenario, fire requirements for building elements are formulated as follows:

- Separating elements shall be designed in ways that sustain a full burnout, thereby preventing uncontrolled spread of fire to other parts of buildings throughout the duration of a fire
- Load-bearing building elements shall be designed in ways that prevent their structural collapse during full burnout without intervention of the fire fighters.

Thus, for tall multi-story timber buildings, the authors put emphasis on the concept of "encapsulation" of the timber structure and/or the use of hybrid structural elements (e.g. timber-concrete composite slabs).

1.2.5 The Case for Tall Wood Buildings

This current interest in tall wood buildings has led to two major feasibility studies for tall buildings. Vancouver architect Michael Green (2012) has produced possible designs for 10, 20 and 30 story timber buildings in *"The Case for Tall Wood Buildings - How Mass Timber Offers a Safe, Economical, and Environmentally Friendly Alternative for Tall Building Structures"*.

The report covers many important aspects of fire safety, but falls short of a clear strategy to meet all the Canadian Code requirements, especially for very tall buildings.

The main thrust for fire safety design is to design in such a way that the timber building can be equivalent to non-combustible construction; that is to achieve "an equal level of performance to that outlined in the acceptable solutions to the Building Code". This is to be achieved with reliance on sprinkler systems, together with the predictable charring rate of heavy timber, and encapsulation where necessary.

The report does not suggest designing for complete burnout of a fire compartment. It covers the possibility of sprinkler failure by providing a 2-hour fire resistance rating to critical structural elements. In extreme events it is expected that "fire department resources would be dispatched and able to suppress the fire condition before the 2-hour fire duration is achieved." It does not adequately cover the case of a post-earthquake fire where the fire-fighting services may be unavailable, other than saying that more research is needed on built-in fire protection systems and their reliability in post-earthquake fire scenarios.

1.2.6 The Timber Tower Research Project

Skidmore Owings and Merrill (SOM, 2013) has produced a feasibility study for a 42 story timber building in Chicago, "*The Timber Tower Research Project,"* based on an existing reinforced concrete tower of the same size. Fire safety is addressed with broad principles but no details. It blithely states that "fire burnout time should be considered" and "fire cannot be allowed to jump between floors" (page 23). It also recommends "flammability tests … to verify that fires will self-extinguish" (page 44). Unfortunately this report does not provide much confidence regarding occupant safety in a 42 story timber building in the event of an unwanted fire, especially if the sprinklers do not work for any reason.

2 Performance-Based Design (PBD)

2.1 Strategy for Fire Safety Design

Performance-based design (PBD) is becoming the long-term objective of code-writers and designers, not only for fire safety. In simple terms this means designing to a target level of performance rather than simply meeting the requirements of a prescriptive building code.

The actual specification and adoption of performance-based design is very different in various countries, depending on the national fire code environment.

PBD for fire safety can mean many different things. For example, any of these could be called PBD:

- Providing the code-specified levels of fire resistance
- Providing the same level of fire safety as the prescriptive code requirements
- Providing a fire safety equivalent to a code-complying steel or concrete structure
- Providing specific levels of fire performance, such as meeting a specified time for escape and/or fire-fighting
- Providing fire resistance to a complete burnout in the absence of fire-fighting

All of these can be specified either on a deterministic basis, or a probabilistic basis using quantified risk assessment tools. Most structural design codes (for non-fire conditions) use a semi-probabilistic approach to provide a design that meets a target failure probability, which could be extended to design for fire safety. Full-scale structural fire risk assessment is still in its infancy, so more research in this area is required (De Sanctis et al., 2014).

The authors of this report suggest that modern building codes should move towards performance-based design for fire safety. A clear definition of performance-based fire design is needed, as this will be of great benefit to code-writers and building designers. Ideally this should have the same basic philosophy for all building materials in all jurisdictions.

2.2 Life Safety Objectives

The over-riding objective of fire engineers is to ensure life safety (occupants and fire fighters). This is achieved either by allowing people to escape, or by protecting them in-place with guaranteed containment of the fire and prevention of structural collapse.

The European Construction Products Directive (CPD) has introduced essential requirements on fire safety that structures must be designed and built such that, in the case of fire:

- Load-bearing capacity can be assumed to be maintained for a specific period of time

- The generation and spread of fire and smoke is limited
- The spread of fire to neighbouring structures is limited
- Occupants can leave the building or be rescued by other means
- The safety of rescue teams is taken into consideration

2.2.1 Building Height

Building height is critical. For low-rise buildings life safety can be achieved by ensuring that all occupants have time to escape the building. Once everyone has escaped, it may be acceptable to allow a building to burn to the ground, depending on the size and value of the building and its contents.

Escape cannot be relied on for tall buildings with many people living or working above the fire floor. For buildings up to about 8 stories (the maximum achievable height of fire-fighting ladders) there is a possibility of fire-fighting and rescue via ladders, but both become very difficult as building height increases above 3 or 4 stories.

The taller the building, the greater the possibility of a fire occurring on an upper floor and people being trapped above the fire floor - a potentially disastrous combination. Tall buildings require a long escape time, and they have slow internal access for fire fighters. It is likely that full encapsulation may be required in order to meet the performance requirements for timber buildings taller than about 8 stories.

If people are to remain safe in tall buildings, it is essential to contain the fire, and prevent structural collapse. If the fire is above the height of fire-fighting ladders, there needs to be total reliance on fire resistance for a complete burnout. There is also danger of vertical fire spread via windows, which is addressed in relation to wooden façade claddings in this report.

This discussion is somewhat beyond the initial scope of the report, but it is included to show the vital importance of providing fire resistance for complete burnout for very tall buildings. This then becomes a critical research need for tall timber structures.

2.2.2 Performance Statements Related to Building Height

Combining the points above, it is suggested that rational performance requirements for all tall buildings should be related to the height of the building and the location with height in the building.

The performance requirements will increase with the height of the building, for the reasons given above. In the most general form, for timber buildings, the requirements might be based on this type of hierarchy:

	Possible level of specified performance:	Possible design strategy for timber elements:
Low-rise buildings	Escape of occupants with no assistance No property protection	No encapsulation

Mid-rise buildings	Escape of occupants with no assistance Some property protection	No encapsulation
Taller buildings	Escape with firefighter assistance Burnout with some firefighting intervention	Limited encapsulation
Very tall buildings	Protect occupants in place Complete burnout with no intervention	Complete encapsulation

The definitions of building height need work, and may be different in different jurisdictions. In all cases, active fire-safety precautions like sprinklers will help to reduce the risk of serious damage, supplemented by on-site water storage in special cases. The level of safety may need to be assessed by a probabilistic fire risk assessment, especially for very large or very tall buildings.

For the very tall buildings, the performance statement might be:

"Very tall buildings shall be designed in such a way that there is a very low probability of fire spread to upper floors and a very low probability of structural collapse, at any time during a fire regardless of whether or not the fire can be controlled by fire-fighting services and/or suppression systems".

2.3 Minimising Property Loss

Property losses are often not included in national building regulations, since the main focus is life safety. However, insurance companies have been increasingly interested in this topic during recent years, since they have insufficient information of property losses in larger and taller timber buildings. The risk for property losses increases with the size of the building.

Property losses are out of scope for this paper, but should be handled separately, preferably by careful risk and cost benefit analysis, leading to additional performance requirements.

2.4 Establishing the Design Level of Fire Resistance

Once the performance requirements have been established, it becomes necessary to provide an appropriate level of fire resistance. Buchanan (2001) outlines four criteria that are considered when determining the level of fire resistance, depending on the size and importance of the building:

- Time for occupants to escape from the building
- Time for fire-fighters to carry out rescue activities
- Time for fire-fighters to surround and contain the fire
- A complete burnout of the fire compartment with no fire-fighter intervention

For very tall or important buildings, the design strategy must be a design for complete burnout of the fire compartment, with no spread of fire to other parts of the building. Design methods (and codification of design methods) for burnout are not well advanced. Some national building codes allow buildings to be provided with levels of fire resistance which would allow failure of the building before complete burnout occurs. For very tall buildings, this could lead to the possibility of some disastrous fires in the future, although the probability is very low if other precautions such as automatic sprinklers are provided.

2.4.1 Design for Burnout

The most common way of designing for burnout is to use a time-equivalent formula to estimate the equivalent fire severity (exposure to a standard fire) for the complete process of an uncontrolled fire from ignition through fire growth, flashover, burning period and decay to final extinguishment. Such time-equivalent formulae assume that the fire severity is a function of the fire load, the available ventilation, and the thermal properties of the surrounding materials of the fire compartment. These values should be determined on a probabilistic basis, with higher safety factors for increasingly tall buildings.

The requirement of safety equivalence has some problems, especially when requiring the equivalence of performance-based design approaches to prescriptive design criteria. The reason is that the safety level of prescriptive approaches depends on building properties and varies for different buildings (De Sanctis et al., 2014).

More research is required to assess the applicability of current time-equivalent formulae for use in multi-story timber buildings. The fire severity, hence the time-equivalent formula, will depend on whether the wood structure has no protection, limited encapsulation or complete encapsulation.

3 Current State-of-the-Art

3.1 Fire-Structure Modeling

Modern structural design methods require the use of sophisticated computer modeling to predict the actions from applied loads or fire exposure, and to predict the capacity of structures and structural members to resist those actions. Large scale or small scale experiments are necessary to calibrate and verify computer models.

The main components of such a model are shown in Figure 1 (Buchanan, 2008). As with all structural materials, any advanced modeling of the fire resistance of timber structures must include both thermal modeling and structural modeling, integrated as far as possible, but all is dependent on an accurate fire model.

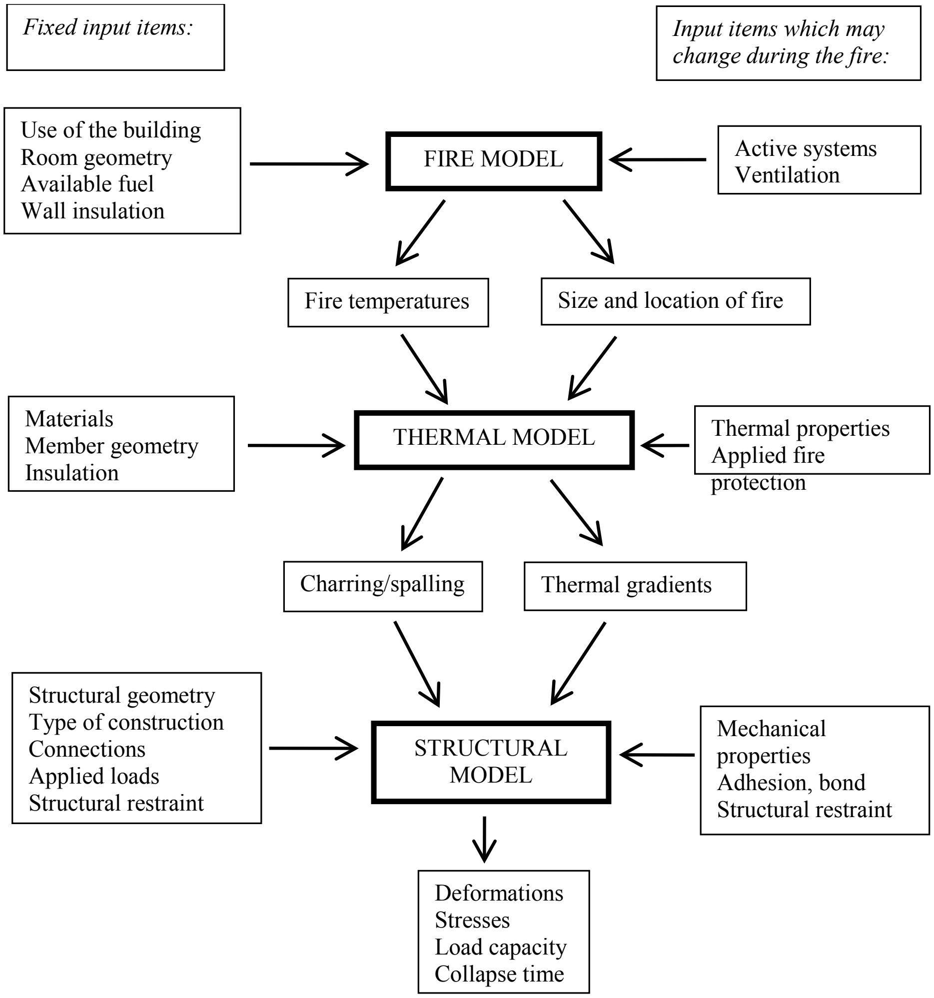

Fig. 1. Flow Chart for Predicting Structural Fire Performance

3.1.1 Fire Model

An accurate fire model is a fundamental part of fire-structure modeling. Accurate models are still not available for post-flashover fires in non-combustible compartments. There is even less accuracy for compartments with combustible structural materials available to fuel the fire. More work on this is proceeding, and any new models will need to be verified with large-scale tests. Results are awaited from Canada of current research "intended to provide fire time-temperature curves that are more realistic to expected fire behavior" (Gerard et al., 2013).

VTT has recently published a report (Hietaniemi & Mikkola, 2010) on design fires appropriate for use in Fire Safety Engineering (FSE) design in general and thus applicable also for buildings with wood. The initial fire growth is quantified using heat release rates which are dependent on the usage of the building. Assessment of fire growth and spread is based on the capability of the FDS fire simulator to make conservative estimations of how rapidly and to how large a fire may grow within a given space. Existing fire models need to be expanded to include changes in ventilation conditions as the fire grows, and to include travelling fires in large spaces. For timber structures, they also need to include the contribution of combustible building materials.

3.1.2 Thermal Model

The thermal model is essential for timber structures exposed to fires, because this is the model which predicts the rate of charring as a function of fire exposure. This is relatively easy for large elements of timber exposed to the standard time-temperature exposure (e.g. ISO 834-1 and ASTM E119) because many tests have shown predictable charring rates for different types of wood products and wood species exposed directly to standard fires. For initially protected timber elements, different charring rates should be applied during different phases of fire exposure, before and after falling off of the protective boards (König and Walleij, 1999). The predictable behaviour of heavy timber in fires allows simple excel calculations based on charring rate to predict the fire resistance of most structural timber elements such as beams, columns, walls and floors. However this is much more complicated for non-standard fire exposure, and for timber structures which are fully or partially protected with other materials. The thermal model needs to allow for the decay phase of the fire, and the possibility or not of self-extinguishment after the available fuel is consumed.

3.1.3 Structural Model

Wood structures are generally easier to structurally model than steel or concrete structures because of the low conductivity of wood and the lack of significant thermal expansion. The heat-affected layer below the char layer is generally very thin (~20-40 mm) so that the structural performance of the wood below this layer is essentially the same as wood at ambient temperatures. Advanced FEM methods are not often required because the simple calculations based on charring are sufficiently accurate.

3.1.4 Summary

The major obstacles to fire-structure modeling in realistic fires are:

1. Knowing the expected temperatures in fully developed fires
2. Knowing the charring rate as a function of fire exposure
3. Knowing the temperature and moisture dependent thermal and mechanical properties of heated timber
4. Knowing the self-extinguishment properties of charred wood
5. Predicting the fire performance and fall-off times of protective systems (e.g. gypsum plasterboards)
6. Predicting story to story fire spread via combustible façade cladding
7. Predicting the effectiveness of details to prevent internal spread of fire
8. Predicting the fire performance of connections between structural timber elements

3.2 Full-Scale Fire-Structure Experiments

Very few large scale experiments have been carried out on large timber buildings. Large scale tests are very expensive, so the objectives of any such tests must be clearly defined before starting. Some of the information needed is summarised above in Section 3.1.4.

Tests have been carried out in several different countries. Unfortunately many of these tests have attempted to answer too many questions, so that the test results are of limited use.

3.2.1 Japanese Tests

Three recent tests on Japanese 3-story school buildings have been performed (Hasemi et al., 2014). The aim was to demonstrate to the national authorities that the fire safety goals can be achieved. This goal seems to have been reached by the latest test (Japanese full-scale fire tests, 2012-2013).

Several full-scale fire tests of whole timber buildings have been performed in Japan in the late 90s, most of them first being subjected to a simulated earthquake (Hasemi, 1989). These tests, mostly of light timber frame buildings protected with gypsum plasterboard, have demonstrated limited fire damage.

3.2.2 Canadian Tests

Tests have been performed in Canada on single rooms constructed from CLT panels (protected and unprotected). Some tests had a second flashover during the decay phase. Results are presented by McGregor (2013).

3.2.3 **European Tests**

Room fire tests with and without encapsulated timber structures were performed in a Nordic project (Hakkarainen, 2002) showing that the room temperature during fire was similar in all cases, but that the non-encapsulated timber structures caused heavy flames out of the windows. These were caused by unburnt gases being produced in the room due to lack of oxygen. Similar results have been obtained in tests performed in Switzerland (Frangi and Fontana, 2005). Further, it was demonstrated that by protecting the timber structure adequately, a complete burnout of the fire compartment with no fire-fighter intervention can be achieved, without any significant damage to the timber structure. A series of tests performed with activated sprinklers confirmed that with a fast response sprinkler system the influence of a combustible structure on the fire safety was compensated and the fire safety objectives can be fulfilled with combustible timber structures. Despite a fast fire development, the structure was undamaged because the sprinkler system extinguished the fire at an early stage.

A full-scale test on a 3-story building made of CLT panels was performed under natural fire conditions to check the global performance and find possible weaknesses of the timber structure (Frangi et al., 2008). The CLT panels were protected by one or two layers of non-combustible gypsum plasterboards. The test confirmed that with pure structural measures it is possible to limit the fire spread to one room even for timber structures. However, the fire was suppressed by the fire-fighting intervention after one hour.

3.3 Experience from Fire Accidents in Timber Structures

Some examples of fire accident types are highlighted in order to supply background information to the need for extended knowledge and research.

3.3.1 Fires after Earthquakes

The biggest danger of fires after earthquakes is the lack of water for fire-fighting and poor access for fire-fighting vehicles. This is a serious threat to timber buildings, especially light timber frame structures. The most well-known recent examples of severe fires after earthquakes are probably the 1989 earthquake in Kobe, Japan, and the 2011 Japanese earthquake and tsunami (Sekizawa et al., 2014). The 2010 and 2011 earthquakes in New Zealand caused very few fires in any kinds of buildings, even though thousands of light timber frame houses suffered severe shaking damage (Baker et al., 2012).

3.3.2 Fires at Construction Sites

Fires at construction sites with timber frame structures have been gaining large publicity recently, mainly in the UK and the US. They seem to have been associated mainly with large areas of construction work without any fire separation and without the final fire protection systems having been installed yet. This topic is not directly included in this report, but as it may influence the further use of timber structures, some guidance should be given.

3.3.3 Fire Spread Caused by Poor Structural Detailing

Structural details in buildings are always very important for the total fire safety of buildings and insufficient detailing may have larger consequences in timber buildings. A recent example is a small kitchen fire at the top floor of a student residential building that caused a total damage of a five story timber building in Sweden. The main reasons were inferior kitchen ventilation, large attic space without fire separation and most importantly insufficient fire stops in the multi story vertical voids between the fire cells.

4 Improving the Fire Performance of Tall Timber Buildings

4.1 Manual Fire Fighting

The risk of severe fires will be reduced if there is prompt action to suppress the fire, either by the building occupants or by the fire brigade. According to EN 1991-1-2 intervention of the fire brigade is considered by reducing the characteristic fire load. This reduction in fire load has been calibrated by Schleich and Cajot (2002) for steel structures, and the same approach could be allowed for structures of any other materials including timber. A similar approach can be used for automatic fire detection or for automatic fire sprinkler systems, as described below. On-site emergency water supplies for manual or automatic suppression systems may also reduce the risk of major losses.

4.2 Sprinklers

Automatic fire sprinkler systems are the most effective way of improving the fire safety in all buildings. They are especially recommended for use in tall timber buildings.

Some building codes (e.g. Switzerland) allow for a reduction in the fire resistance if automatic fire sprinkler systems are installed. A reduction of fire resistance to 60% of the normal value is included in Eurocode 1 for sprinklered buildings. For an individual building owner this may be important, but the potential benefits of sprinklers require a quantitative fire risk assessment be taken into account, also including risks from earthquakes, maintenance, and an overwhelmed water system. The New Zealand Building Code allows a 50% reduction in fire resistance for sprinklered buildings under certain conditions.

It should be noted that the reliability of sprinkler systems usually are much higher than for many systems of passive fire protection, fire doors probably being the most obvious example with reliability levels down to 70% (BSI PD, 2013). Sprinkler installations may also allow for a wider use of visible wood on internal and external building surfaces. This has been verified by risk analysis (Nystedt, 2011, 2012).

4.3 Encapsulation

The FP Innovations report (2013) and the IABSE SED (Smith and Frangi, 2014) give a lot of emphasis to encapsulation, in two categories, either complete encapsulation or limited encapsulation. The purpose of encapsulation is to ensure that structural timber does not contribute to the fire load, and also to ensure that the fire does not continue to burn after the combustible contents of any fire compartment have been completely burned away. The Japanese concept of “Fire Resistive Construction” has similar objectives, as explained in Section 5.4.

4.3.1 Complete Encapsulation

Complete encapsulation provides sufficient thickness of gypsum plasterboard or other similar material to prevent any charring of the wood in a complete burnout, thereby providing the same level of fire resistance as a totally non-combustible material. It is suggested in FPInnovations (2013) that two layers of Type X gypsum board will prevent the onset of charring for 2.0 hours exposure to the standard fire, giving total fire resistance of up to four hours in many cases. This claim needs to be verified because it depends on the thickness, the fixing details, and they type of gypsum board.

4.3.2 Limited Encapsulation

Limited encapsulation is a more economical solution which will prevent any involvement of the structural timber in the fire until well into the burning phase, but may not guarantee complete burnout with no onset of charring.

4.3.3 Layered Encapsulation

Layered encapsulation refers to timber structural elements made up of layers of wood and non-combustible materials. In some cases this may be a timber member with limited encapsulation, covered with an additional wood layer to improve the appearance and the fire resistance. Many different combinations of materials are possible, all requiring more research and testing.

4.4 Fire Performance and Fall-Off Times of Protective Systems

Protective layers such as gypsum plasterboards are often used to protect timber structures from fire. For the verification of fire resistance, full-scale testing or calculation using design models can be used. The latter needs input values which describe the contribution of the cladding (lining) to the overall fire resistance of the construction. Fall-off time of the cladding is one of the parameters needed, but it is seldom monitored properly in full-scale fire tests, although it has large impact on the fire resistance (Just et al., 2010). Further, fall-off time of the cladding based on standard time-temperature exposure (e.g. ISO 834-1 and ASTM E119) may not reflect the fire behaviour for non-standard fire exposure (Frangi et al., 2008).

A related problem is the variability between different types of gypsum plasterboard from different manufacturers in different countries. The contribution to the fire resistance of gypsum plasterboards is not specified in standards such as the European product standard for gypsum plasterboards (EN 520) or for gypsum fibreboards (EN 15283) nor the design standard for timber structures, Eurocode 5, part 1-2, (EN 1995-1-2). Hence important characteristics are lacking as input for the design models.

A methodology (routine) has to be developed to obtain input values for design models, such as the model in the fire part of Eurocode 5. These need to be verified by full-scale tests. The methodology developed should be implemented in an official document (e.g. national or international standards) and used by notified bodies to certify material characteristics not covered by other standards. Currently, a European standard (prEN 13381-7) is under development, providing test methods for determining the contribution to the fire resistance of applied protection (e.g. gypsum plasterboards) to timber structural members.

4.5 Fire Performance of Connections between Structural Timber Elements

Prior to the 1990s, knowledge of the fire performance of timber connections was limited. At that time, there was no method for assessing the behaviour of wood joints exposed to fire, nor for calculating their load carrying capacity in fire (Carling, 1989). In the last two decades, this area has received large attention and several research efforts have been devoted to the analysis of the fire performance of timber connections. So far, extensive experimental and advanced numerical studies have been performed (Noren, 1996; Moss et al., 2009; Cachim and Franssen, 2009; Erchinger et al., 2010; Frangi et. al., 2010; Peng et al., 2010, Audebert et al., 2013); however, simple models for design in fire are still limited. Further, current knowledge is limited to standard time-temperature exposure (e.g. ISO 834-1 and ASTM E119).

4.6 External Fire Spread

The main risk for external fire spread is from big flames coming out of windows in a fully developed compartment fire and spreading upwards along the façade. Such flames usually reach the story above independent of building material and this is accepted in most building regulations. But there is no consensus or procedures on how to determine the risk for the external flames reaching two stories above the compartment fire. The issue is handled differently and only on a national basis. For timber structures, the main interest is to verify that wooden facades can be used in a fire safe way, also as façade claddings on, e.g., concrete or steel buildings.

There are also risks for fire spread between adjacent buildings. These risks are considered to be independent of the structural building system used, although the contribution of combustible cladding materials should be included.

4.7 Details to Prevent Internal Spread of Fire

The execution of construction works is critical to good building performance; inappropriate practices can lead to critical building damage, which can generally only be rectified at considerable financial expense.

In order to achieve the required fire safety level, the fire behaviour of the building construction, service installations, and additional safety measures must be reviewed and assured. The evaluation factors are interlinked, and interfaces (assembly of wall or ceiling configurations) with related fire resistance requirements as well as reaction to fire performance of encapsulated combustible load-bearing structure must be quantified.

Fire spread can be minimized with internal fire stops as well as at interfaces, for example with penetration seals for the electric installation or heating systems, or additional safety measures such as preventive structural measures, but also the application of specific active fire protection systems such as sprinklers or smoke detectors.

Connections of wall, ceiling and roof elements have a significant influence on the fire behaviour, the danger being uncontrolled spread of smoke, hot gases and fire. Poorly designed connections affect evacuation, life, and property safety (e.g. spread of CO to neighbouring rooms).

Penetrations through fire-rated walls and floors for ventilation, pipes and other building services can provide paths for spread of fire and smoke. Careful attention to detailing and quality control is required.

5 Knowledge Gaps

Knowledge gaps are explored below, based on the text above.

5.1 Data on Actual Fires

There is a lack of statistical information on the fire performance of real timber buildings, in all countries. In order to develop probabilistic design methods, it is necessary to have data on the number and severity of fires, and the effectiveness of automatic and manual fire suppression.

5.2 Full-Scale Experiments

Many more full-scale tests are needed to provide information on fire severity. These must be large scale, so they will be expensive. Because of the trend to multi-story timber buildings, it is important to address the influence of combustible materials carefully, in particular when no encapsulation or sprinklers are provided. Some examples are given:

- Determine the contribution of massive timber elements (e.g. CLT) to fire severity for non-standard fire exposure (interesting also for standard fire exposure)
- Determine fall-off times of claddings for non-standard fire exposure (also required for standard fire exposure)
- Determine the load bearing capacity and stability at fire exposure of timber building elements 3-10 m high – interesting also for standard fire exposure
- Determine the relevant fire exposure conditions for different types of fire stops in voids in timber structures
- Determine the influence of wooden façade claddings on the exterior fire spread of multi-story buildings with flames coming out from a broken window after flashover
- Determine the influence of active (e.g. sprinkler) fire protection on structural fire performance and external spread of flame in a building

5.3 Small-Scale Experiments

Small-scale experiments are needed to:

- Establish the charring rates of different types of wood and wood-based products under different levels of thermal radiation
- Establish the self-extinguishment properties of different types of wood and wood-based products after different levels of fire exposure
- Determine the performance of different types of fire stops according to fire exposure conditions and procedures to be determined, see above
- Determine the performance of different types of connections according to fire exposure conditions and procedures to be determined, see above
- Investigate the charring rates of engineered wood products such as glulam, CLT, LVL and hybrid products, considering the effects of any gaps and the effects of different types of adhesive

5.4 Evaluation of Existing Fire Testing Experience

Japan has requirements on extended time after fire resistance testing of combustible structures in order to evaluate possible continued charring and loss of load-bearing capacity. Their experience should be consulted before starting further studies on this topic.

In summary, Japanese building codes have been adapted to ensure self-extinguishment of certain types of timber elements, and fire testing methods have been modified to assess the performance of encapsulation and self-extinguishment. Two types of fire resistance grade are defined in Japan:

1. "Fire Resistive Construction" requires structural stability of structural elements during and after a fire, including the entire cooling phase.
2. "Fire Preventive Construction" and "Quasi-fire Resistive Construction" both require structural stability for a specific fire duration. For example, 30 min, 45 min, or 60 min.

Fire resistance tests of "Fire Resistive Construction" must demonstrate the self-extinguishment of structural timber elements. The duration of each fire test depends on the type of material. If the structural elements are non-combustible material, a 3 hour cooling phase is nominally required after a 1 hour fire resistance test. If the structure is combustible, the duration of the cooling phase might be as long as 24 hours. Test operators in fire laboratories do not pre-determine the duration before the fire tests, because they will only stop the test when charred wood of the specimen do not glow and the temperatures of all measurement points decrease below the decomposition temperature of the material.

5.5 Modeling

5.5.1 Fire Models

Existing fire models need to be expanded to include changes in ventilation conditions as the fire grows, and to include travelling fires in large spaces. For timber structures, they also need to include the contribution of combustible building materials.

5.5.2 Simple Thermal Models

Simple thermal models can be used for the design of large timber structures provided that the charring rate of wood is known under different thermal exposures. The charring rate is well known under standard fire exposure but it is important to know the change in charring rate under more realistic fire exposure. More research, including large scale experiments, is required to provide the charring rates needed for simple calculation models to be applied to realistic fires.

5.5.3 Advanced Thermal Models

Advanced thermal modeling can be done using the finite element method (FEM). These advanced methods are important for the development of simple charring models, but they are not normally required for design. For development of more advanced thermal calculation models, the problem is obtaining accurate time-dependent and temperature-dependent thermal properties of materials.

5.5.4 Advanced Structural Models

Complete fire-structure modeling based on FEM requires coupled thermal and mechanical analysis, which is difficult because of the large number of unknown input values. For standard ISO fire exposure tremendous improvements have been achieved (O'Neill et al., 2014; Schmid et al., 2010; and Klippel, 2014). However much needs to be done to provide accurate input data before the performance of timber structures exposed to natural fires can be predicted accurately.

The development of more advanced structural calculation models requires accurate time-dependent and temperature-dependent mechanical properties of wood-based materials.

5.6 Performance-Based Design

An international agreement is needed on the overall approach of performance-based design (PBD) for fire safety (and fire resistance), consistent for all materials. It should be based on design fires for different types and sizes of buildings and occupancies. This needs to include the development of probabilistic or semi-probabilistic design methods for fire safety, to encourage building designs that meet target failure probabilities specified in modern building codes.

6 How Best to Address the Seven Focused Topics in the Scope of Work

6.1 Identify R&D Needs for Large-Scale Experiments

Large-scale experiments on timber structures are needed to support PBD and structure-fire model validation. The main needs are to develop a design strategy for "burnout of fire compartments" to prevent structural collapse and to control vertical spread of fire, also to understand the interaction between active and passive fire protection systems. This needs to be focused on the development of advanced computer modeling, followed by, and supported by, experiments.

6.2 Prioritized Needs in Order of Importance

1. Agreement on relevant design fires / parametric fires to be used for the structural fire performance of buildings – these should be the same for all structural materials.
2. Determine the contribution of massive timber elements (e.g. CLT) to fire severity for non-standard fire exposure.
3. Determine charring rates as a function of fire exposure (design fires) – does not need large scale facilities.
4. Determine conditions for self-extinguishment of charred wood, and reusability of the timber structure after a fire. This will require tests to compare the relative performance of different species and products.
5. Determine the performance of encapsulated timber elements, including the fall-off times of protective boards for non-standard fire exposure.
6. Determine the performance of different types of connections for non-standard fire exposure.
7. Determine the relevant fire exposure conditions for different types of fire stops in voids in timber structures.
8. Determine the influence of wooden façade claddings on the exterior fire spread of multi-story buildings with flames coming out from a broken window after flashover in an apartment.

9. Determine the influence of passive (e.g. non-combustible claddings) and active (e.g. sprinkler) fire protection on the items above.
10. Quantitative fire risk assessment to determine the balance between active and passive fire safety measures in tall timber buildings.

6.3 Recommended Timeline

All of these items are urgent. They should be investigated as soon as there is money available.

6.4 The Most Appropriate International Laboratory Facilities

It is very important to distinguish between standard fire test facilities (mainly for commercial tests of building elements) and non-standard facilities (for research of whole buildings or parts of buildings).

Every country has standard fire test facilities, and results are largely transferable between labs because all the international standards for fire resistance are similar. These facilities can be used for much of the research testing required.

Large-scale special-purpose research testing is required on an international scale, with test results shared between countries. Test facilities for large-scale special-purpose research testing are much more difficult to find. In North America, large scale laboratory facilities are available at NIST, also at FM Global, the National Research Council of Canada, and Carleton University in Ottawa. Other large scale testing facilities are available in France, Japan, and Australia. Some facilities used in the past are no longer available, such as those at Cardington in the UK.

Very large special purpose testing may be carried out in the open, not needing huge laboratories. This has been done recently in Japan, with destructive tests on several three-story timber school buildings.

6.5 Potential Collaborators and Sponsors

6.5.1 Collaborators

Potential collaborators include: university and government researchers (national and international), international conferences, the “Structures in Fire (SiF) community, and ISO meetings.

6.5.2 Sponsors

Potential sponsor include: US timber industry, Canadian suppliers, insurance industry, and government funding aimed at promoting sustainable development of the construction sector.

6.6 Transfer of Results to Industry

6.6.1 Specific National and International Standards

It will be very useful to have international guidance on ways to fulfil different requirements based on international standards for specific national codes. Codes must be based on a scientific response to consistent objectives. It will be easiest to start with Europe where a harmonised system for requirement classes and methods is in force, even if the different countries still may choose different levels of performance.

It is essential to maintain international standardisation, through organisations such as the International Standardisation Organisation (ISO), in particular ISO TC 92.

6.6.2 Predictive Tools for Use in Practice

The hard part is establishing the performance requirements. Once those are in place, a fire model and a structural model are both needed. The development of an accurate fire model for realistic fires needs experimental research. Once the fire model has been developed, and the charring rates established, the structural calculation tools can be relatively simple for wood, provided that the necessary input data is available.

6.6.3 Comprehensive Research Reports

All test and research results must be supported by comprehensive research reports. These will provide the international guidance needed to develop national and international standards. All reports must include case study buildings and worked examples.

6.6.4 Quality Assurance

Quality assurance is essential, at many levels, if research results are to produce safer buildings. This includes design calculations and specifications, documentation of designs, code enforcement and inspection of on-site construction.

Timber frame construction often consists of a combination of several different materials, which are designed and installed to fulfil multiple performance functions such as fire safety and acoustic performance. The methods used for assembling/erecting these multiple layers are vital to ensuring adequate performance. The sourcing and manufacture of all materials must meet the specified requirements.

Although the assembly sequences may differ, the requirements for ensuring adequate performance levels are identical. As an example, insulation (e.g. mineral wool) must be mounted carefully and must be in direct contact with wooden beams and girders to ensure adequate fire performance. Empty voids can lead to premature exposure of wooden elements in the event of a fire, and can lead to earlier charring and therefore decreased fire resistance. Careful installation of insulating products is particularly important in nominally empty attic areas, where the insulation can tend to be less carefully installed due to the non-occupied state of the roof space.

Fasteners used for securing claddings are also essential for the fire resistance. If nails or screws are too short, the cladding will be prone to premature delamination (fall-off), and wooden beams and girders will be exposed to fire at an earlier stage. This will lead to earlier charring and can reduce fire resistance times.

The installation of fire stops within the building as well as in façade gaps or voids, the erection and connectivity of penetrations and building services systems at the construction site are essential to ensure the fire performance of a timber structure. The appropriate installation of such details can be checked only during the construction period, and the quality of workmanship of such details should be monitored closely by the responsible contractor.

Self-monitoring by the contractor is an important process, and should be mandated and formalised whenever possible. The responsibilities of interacting trades must be clearly stated, and overarching project management processes communicated and enforced at the beginning of a project. In larger buildings third party control by building inspectors is essential.

6.7 International Coalition to Review Progress

The international coalition should be built on the existing network FSUW, Fire Safe Use of Wood. FSUW is originally a European network with mainly research and industry partners. The main result so far from FSUW is the very first European guideline on Fire Safety in Timber Buildings (Östman et al, 2010). The network has recently been extended to include partners from Australia, Canada, Japan and New Zealand and should be further extended to include US participants.

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