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FIRE SAFETY ENGINEERING – OPPORTUNITIES AND CHALLENGES FOR TIMBER BUILDINGS

Birgit Östman[1], Daniel Brandon[2]

ABSTRACT: The combustibility of timber is one of the main reasons that many building regulations strictly limit the use of timber as a building material. Fire safety is an important contribution to feeling safe, and an important criterion for the choice of building materials. The main precondition for an increased use of timber in buildings is adequate fire safety. This paper reviews the opportunities and challenges to reach this goal by implementing Fire Safety Engineering and Performance Based Design principles.

KEYWORDS: Fire Safety Engineering, Life safety, Property loss prevention, Performance Based Design

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. Novel fire design concepts and models have been developed, based on extensive testing. The current improved knowledge in the area of fire design of timber structures, combined with technical measures, particularly sprinkler systems, and well-equipped fire services, allow the safe use of timber in a wide field of applications. 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. 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 NATIONAL DIFFERENCES

Fire test and classification methods have been harmonised in Europe, but regulatory requirements remain on national bases. Although the European standards exist on the *technical level*, fire safety is governed by national legislation, and is thus on the *political level*. National fire regulations therefore remain, but new principles for Fire Safety Engineering create opportunities and challenges for harmonised views.

Major differences between European countries have been identified, both in terms of number of storeys permitted and of visible wood surfaces in interior and exterior applications [1, 2], see Figure 1.

Several countries have no specific regulations, or do not limit the number of storeys in timber buildings. However, a maximum of eight storeys is often used as a practical and economic limit for timber structures. This limit may be higher for facades, linings and floorings, since these applications may also be used in, for example, concrete structures.

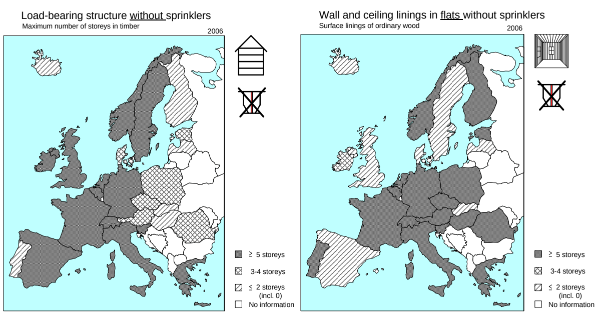

***Figure 1**: Restricted use of timber structures and visible wood set by national prescriptive regulations [1, 2]. Dark colours indicate that ≥ 5 storeys are allowed.*

[1] Birgit Östman, SP Technical Research Institute of Sweden, birgit.ostman@sp.se
[2] Daniel Brandon, SP Technical Research Institute of Sweden, daniel.brandon@sp.se

1.2 RECENT STUDIES

1.2.1 European guideline

The very first European guideline on Fire Safety in Timber buildings [1] was produced by a multi-national team. 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 guideline refers mainly to fulfilling requirements according to the European system for fire safety in buildings, but the basic principles are all applicable world-wide.

This guideline 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 North American review

The Fire Protection Research Foundation [3] has published an extensive literature review and case studies of modern timber buildings around the world. It includes a comprehensive gap analysis, leading to recommendations for future research and testing:

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

A phase 2 of this project is ongoing with the goal to quantify the contribution of Cross Laminated Timber (CLT) building elements in compartment fires and evaluate the relative performance of CLT systems compared to other buildings systems commonly used in tall buildings.

1.2.3 Canadian guide

FPInnovations has published a technical guide for the design of tall wood buildings [4]. The fire chapter covers much of the same material from a Canadian perspective. It is strongly related to the objective-based National Building Code of Canada (NBCC), with 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 draws attention away from the basic principles of fire safety design.

The guide gives recent examples of heavy timber construction in Canada, with useful sections on the fire resistance of penetrations and concealed spaces, façade spread, and a summary of fire risk assessment methods.

The guide promotes “complete encapsulation” of wood to provide fire safety equivalent to non-combustible steel or concrete construction.

1.2.4 International document

The International Association for Bridge and Structural Engineering (IABSE) has published a Structural Engineering Document (SED) on the Use of Timber in Tall Multi-Storey Buildings [5]. The document addresses a reawakening of interest in timber products as primary construction materials for relatively tall, multi-storey buildings. Emphasis is on the holistic addressing of various issues related to performance-based design of completed systems, reflecting that major gaps in knowhow relate to design concepts rather than technical information about timber as a material.

Special consideration is given to structural and durability aspects for attaining desired building performance over lifespans that can be centuries long. It includes 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. Based on this scenario, fire requirements for building elements are formulated as:

- Separating elements shall be designed to sustain a full burnout
- Load-bearing building elements shall be designed to prevent their structural collapse during full burnout.

1.2.5 NIST White paper

A white paper focussing on the fire resistance of timber structures [6] has been published. It attempts to define a Performance-Based framework for the fire safety design of multi-storey timber buildings. The report concentrates on medium-rise multi-storey timber buildings from 3 to 10 storeys, which are likely to be most popular and technical feasible. It concentrates on “mass timber” buildings, constructed from large timber posts and beams and large wood panel construction using cross-laminated timber (CLT) or other heavy timber panels and on the fire resistance of those elements and assemblies. 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 storeys.

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.

1.2.6 Case study for Tall Wood Buildings

Possible designs of 10, 20 and 30 storey timber buildings is published in the feasibility study [7]. The study 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 study 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.

1.2.7 Case study on Timber Tower

Another feasibility study for a 42 storey timber building in Chicago [8] is 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". It also recommends "flammability tests … to verify that fires will self extinguish". Unfortunately this study does not provide much confidence regarding occupant safety in a 42 storey timber building in the event of an unwanted fire, especially if the sprinklers do not work for any reason.

2 FIRE SAFETY ENGINEERING - FSE

Fire Safety Engineering and performance based design create opportunities and challenges for harmonised views on timber buildings. A performance-based approach to fire safety design relies on the use of fire engineering principles, calculations and/or appropriate modelling tools to satisfy building regulations. Instead of prescribing exactly which protective measures are required, it is the required performance of the overall system that is presented against a specified set of design objectives.

The main principle in applying performance-based requirements is that the building shall be designed and executed on the basis of design fire scenarios, which must cover the conditions which are likely to occur in the building. The following objectives must be shown to be fulfilled:

- Load-bearing capacity must be maintained for a minimum period of time
- Generation and spread of fire must be limited
- Fire spread to neighbouring buildings must be limited
- Occupants must be able to leave the building
- The safety of rescue teams must be considered.

This leads to the need for defining criteria to satisfy life safety objectives (safety of occupants and rescue teams) and criteria for loss prevention.

National building regulations may define performance criteria to be applied in structural fire safety engineering design, such as:

- A building of more than two storeys must not collapse during the fire or cooling phase, *or*
- A building of not more than two storeys must not collapse during the period of time required for securing evacuation, rescue operations and controlling the fire.

Performance-based regulations and standards have long been proven an effective way to facilitate innovation. A Nordic system was developed already in the 90-ties [9] and international standards are available [10]. However, several necessary elements are needed to ensure a creative yet robust environment. Unlike prescriptive regulation, performance based regulations do not specify how to achieve fire safety, thus allowing a variety of different possible solutions. New verification methods exist and new research provides a common basis for the implementation of innovative methods. In order to develop a more practical approach for FSE, Nordic standards are being developed [11] to facilitate innovation, freedom of trade but also consistency.

3 PERFORMANCE BASED DESIGN - PBD

3.1 STRATEGY FOR FIRE SAFETY DESIGN

Performance based design 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 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.

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.

3.2 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.

3.2.1 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 storeys (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 storeys.

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 storeys.

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, that is not addressed in this paper.

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

Table 1: *Possible hierarchy of requirements*

	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 [16]:

"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".

3.3 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 and limited technical expertise. They therefore fear both larger property losses and water damages in timber buildings. The risk for property losses increases with the size of the building. Strategies to verify loss prevention measures need to be developed.

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.

3.4 ESTABLISING DESIGN LEVEL OF FIRE RESISTANCE

Once the performance requirements have been established, it becomes necessary to provide an appropriate level of fire resistance. Four criteria have been defined [6] for 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.

3.4.1 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.

More research is required to assess the applicability of current time-equivalent formulae for use in multi-storey 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.

4 CURRENT STATE OF THE ART

4.1 PRESCRIPTIVE REQUIREMENTS

Fulfilling prescriptive requirements on fire resistance and reaction to fire performance in national building codes is easy, either by known performance e.g. in [1], by fire testing according to established standards or by calculating according to design codes e.g. [12].

4.2 MODELLING

Modern structural design methods require the use of sophisticated computer modelling 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 2 [6]. As with all structural materials, any advanced modelling of the fire resistance of timber structures must include both thermal modelling and structural modelling, integrated as far as possible, but all is dependent on an accurate fire model.

4.2.1 Fire model

An accurate fire model is a fundamental part of fire-structure modelling. 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. More work is proceeding, and any new models will need to be verified with large-scale tests.

VTT has published a report [13] on design fires appropriate for use in Fire Safety Engineering 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 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 travelling fires in large spaces. For timber structures, they also need to include the contribution of combustible building materials.

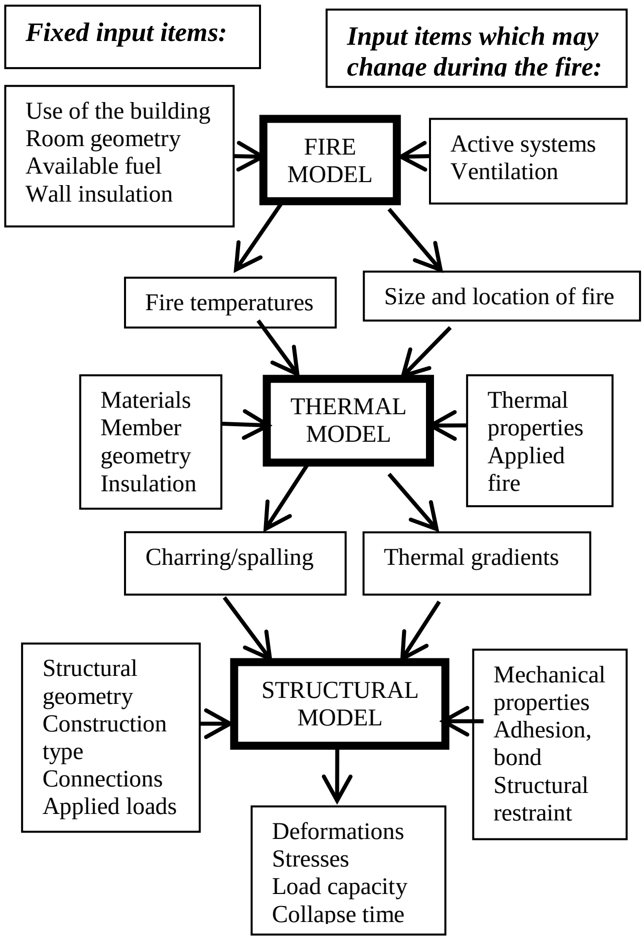

Figure 2*: Flow chart for predicting structural fire performance* [6]

4.2.2 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 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 [12]. 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.

4.2.3 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.

4.2.4 Modelling summary

The major obstacles to fire-structure modelling in realistic fires are knowing the

1. expected temperatures in fully developed fires.
2. charring rate as a function of fire exposure.
3. temperature and moisture dependent thermal and mechanical properties of heated timber.
4. self-extinguishment properties of charred wood.

and predicting the

5. fire performance and fall-off times of protective systems (e.g. gypsum plasterboards).
6. storey to storey fire spread via combustible façade cladding.
7. effectiveness of details to prevent internal fire spread
8. fire performance of connections between structural timber elements.

4.3 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. Unfortunately many of the tests performed have attempted to answer too many questions, so that the test results are of limited use.

4.3.1 Japanese tests

Three recent tests on Japanese 3-storeys school buildings have been performed [14]. The aim was to demonstrate to the national authorities that the fire safety goals can be achieved and have been reached by the latest test.

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

4.3.2 Canadian tests

Tests in Canada on single rooms constructed from CLT panels. Protected and unprotected structures were included. Some tests had a second flashover during the decay phase [15].

4.3.3 European tests

Room fire tests with and without encapsulated timber structures were performed in a Nordic project [16] 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 [17]. 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 on the timber structure. A series of tests performed with activated sprinkler confirmed that with fast response sprinklers the influence of a combustible structure on the fire safety was compensated and the fire safety objectives can be fulfilled with combustible timber structures.

A full-scale test on a 3-storey building made of CLT panels was performed under natural fire conditions to check the global performance and find possible weaknesses of the timber structure [18]. 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. However, the fire was suppressed by the fire-fighting intervention after one hour.

4.4 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.

4.4.1 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 [19]. 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 [20].

4.4.2 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 not yet being installed. 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.

4.4.3 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 storey 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 storey vertical voids between the fire cells.

5 IMPLEMENTING FIRE SAFETY DESIGN IN TALL TIMBER BUILDINGS

5.1 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 Eurocode 1 [21] intervention of the fire brigade is considered by reducing the characteristic fire load. This reduction in fire load has been calibrated [6] 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, see below. On-site emergency water supplies for manual or automatic suppression systems may also reduce the risk of major losses.

5.2 SPRINKLERS

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

Some national 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 [21] for sprinklered buildings. For an individual building owner this may be important, but the potential benefits of sprinklers require a quantitative fire risk assessment 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 passive fire protection systems, fire doors probably being the most obvious example with reliabilities down to 70 % [22].

5.3 ALTERNATIVE FIRE DESIGN BY SPRINKLERS

Sprinklers save lives. In addition, sprinklers may allow for an alternative design of buildings. Requirements on passive fire protection to provide means of safe egress may be at least partly reduced, see Figure 3. This will facilitate a more flexible use of wood products.

The implementation of alternative fire safety design with sprinklers may vary between countries. In Sweden fire design alternatives have been verified [23], including wooden façade cladding and wood panels as interior surface linings in multi-storey buildings.

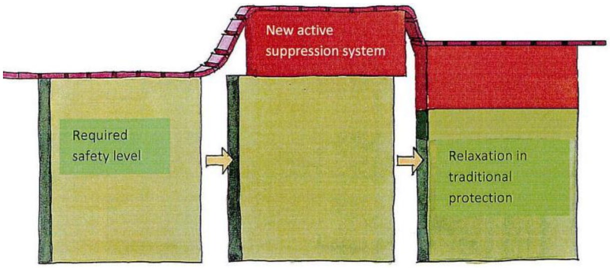

Figure 3: *Principle for fire safety design by sprinklers: Increased fire safety by installation of sprinklers may lead to relaxations in the passive fire protection features, and still fulfil the same or higher safety level [23].*

5.4 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, see 6.4.

5.4.1 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.

5.4.2 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.

5.5 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 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 [24]. Further, fall-off time of the lining based on standard time-temperature exposure may not reflect the fire behaviour for non-standard fire exposure [18].

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 or for gypsum fibreboards nor the design standard for timber structures [12]. 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 [12]. 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 [25] 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.

5.6 FIRE PERFORMANCE OF CONNECTIONS BETWEEN STRUCTURAL TIMBER ELEMENTS

Knowledge about the fire performance of timber connections has been limited, but 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. Extensive experimental and advanced numerical studies were performed [6]; however, simple models for design in fire are still limited. Further, current knowledge is limited to standard time-temperature exposure.

5.7 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 storey 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 storeys above the compartment fire. The issue is handled differently and only on 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.

5.8 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 preventative 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.

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.

5.9 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.

Fixings 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 R&D NEEDS TO REACH FSE AND PBD

6.1 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,

6.2 FULL-SCALE EXPERIMENTS

More full-scale tests are needed to provide information on fire severity. Because of the trend to multi-storey 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 to determine the

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

In addition, small-scale experiments are needed to determine the charring rates and self-extinguishment properties of wood-based products after different levels of fire exposure, performance of different types of fire stops according to fire exposure conditions, performance of different types of connections and charring rates of engineered wood products such as glulam, CLT, LVL, considering the effects of different types of adhesives.

6.3 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, 45 or 60 minutes.

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, 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 do not glow and the temperatures of all measurement points decrease below the decomposition temperatures.

6.4 MODELLING NEEDS

6.4.1 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.

6.4.2 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.

6.4.3 Advanced thermal models

Advanced thermal modelling 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- and temperature-dependent thermal properties of materials.

6.4.4 Advanced structural models

Complete fire-structure modelling based on FEM requires coupled thermal and mechanical analysis, which is difficult due to the large number of unknown input data. For standard ISO fire exposure tremendous improvements have been achieved [26, 27]. 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.

6.5 PERFORMANCE BASED DESIGN - PBD

An international agreement is needed on the overall approach of performance based design for fire safety, 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.

6.6 NATIONAL AND INTERNATIONAL STANDARDISATION

International guidance on ways to fulfil different requirements based on international standards is needed. Codes must be based on a scientific response to consistent objectives. The international standardisation should be maintained mainly through the International Standardisation Organisation (ISO), in particular ISO TC 92. It is also essential to maintain and further develop a close contact to national fire authorities.

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 is the very first European guideline on Fire Safety in Timber Buildings [1]. The network has recently been extended to include partners from Australia, Canada, Japan and New Zealand and should be further extended to include the US.

7 FINAL COMMENTS

Fire safety engineering and performance based design offer a lot of benefits and opportunities for increased timber building, e. g. a more harmonised view on how to fulfil national fire requirements and insurance requirements. This will remove or reduce the still existing obstacles to trade within Europe and worldwide and also facilitate for a more globalised market. This should be the long term strategy for timber buildings.

There are also a lot of more short term challenges to overcome. The most important are to ensure

- Quality of construction workmanship and inspection and Fire safety during construction, since proper detailing is the main challenge to reach fire safety
- Control of the main strategies to reach property loss prevention in relation to other types of buildings
- Control of the main strategies to avoid collapse of the building in case a fire is not extinguished by an automatic active system or by the fire services.

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