A SIMPLIFIED DESIGN METHOD FOR ESTIMATING THE FIRE PERFORMANCE OF STRUCTURAL TIMBER FLOORS

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ABSTRACT

The widespread use of structural timber in tall buildings is often inhibited because timber is a combustible material and is commonly perceived to behave poorly in fires. This research develops a simplified design approach for the fire performance of different types of prefabricated timber floors used in multi-storey buildings. The floor types under investigation include several different geometries of box-shaped and T-shaped timber floors made from Laminated Veneer Lumber (LVL). The investigations were carried out with numerical simulations and four experimental fire tests. A simplified design method to estimate the fire resistance of unprotected timber floor assemblies is proposed and calibrated against the numerical and experimental work. The method uses a bi-linear charring rate and the assumption of a zero strength layer in the timber. The method is compared to the experimental data from this research and others around the world, as well as charring rate methodologies from around the world.

KEYWORDS

Fire, timber, floors, furnace testing, design methods.

INTRODUCTION

Timber as a building material provides high levels of flexibility in terms of building design, and a freedom of architectural expression. It is aesthetically pleasing, making it an ideal material for use in environments where there is a desire to promote a sense of warmth and wellbeing, such as modern commercial and residential applications. As timber is also highly sustainable, it has distinct advantages over conventional building materials in an increasingly socially and environmentally conscious building environment. However as timber is combustible, the question of fire safety is paramount in the discussion of its application in large multi-storey buildings.

When considering the fire performance of timber structures in the built environment, restrictions are commonly placed on the allowable height of a building, to reduce the perceived risk of an unacceptable fire hazard stemming from the combustible nature of the material. This perceived risk can be broadly defined as the risk of catastrophic collapse or fire spread throughout the building and to other buildings, posing a threat to both the general public and property alike. This inhibits the widespread use of timber in large developments due to the perception of poor performance in fires. In reality, massive timber structures often exhibit excellent fire performance due to the inherent insulative properties of timber as a material. Timber assemblies have been demonstrated in the past to provide and maintain loadbearing and separating functions during prolonged periods of fire exposure. As many of the new timber technologies which are becoming prevalent in our markets have not yet been properly implemented into building codes, it is becoming increasingly important to provide evidence and guidance on their expected performance in fires to enable the correct use and implementation in the built environment.

Impetus of the Research

Floor systems provide the means for directly supporting the primary service loads of a building. In terms of fire, they also provide the separation between compartments. Most floors have large unprotected surfaces that are exposed to fires, and are thus regarded as critical elements in designing for the structural fire resistance. As timber is a combustible material its fire performance is complicated by the loss of its cross-section due to charring, the anisotropy of the material itself and the presence of connections. Thus adequate guidance and design procedures are paramount to ensure that floor systems are appropriately designed and installed in modern buildings. In consideration of this, the impetus behind this research is to provide information and guidance on the estimation of fire resistance for standardised prefabricated timber floor assemblies used in multi-storey buildings. This work is based on experimental testing, numerical modelling, and studies of available design procedures to develop a simplified design method to estimate fire resistance of timber floors.

FLOOR TYPES STUDIED

The floor types under investigation include several different geometries of box-shaped and T-shaped timber floors made from Laminated Veneer Lumber (LVL), shown in Figure 1.

Figure 1 Illustration of composite box-shaped LVL floor (left) and composite T-shaped LVL floor (right)

The floors consist of LVL joists 200 mm to 600 mm deep, fixed to a continuous LVL slab system, with a fully rigid connection between the joists and slab components. Typically these floors range from 5 metres to 12 metres in length and are designed for normal service loads in office buildings and similar multi-storey buildings.

FURNACE TESTING

Floor Specimen Details

Four timber floor assemblies (two lightweight and two heavyweight variants) were tested in a full-scale furnace under controlled conditions at the Building Research Association of New Zealand (BRANZ), Wellington. These floors were sized to give approximately 30 and 90 minute fire resistance times, using generic LVL member sizes available from the manufacturer (Nelson Pine LVL 2012).

Specimens A and B were smaller T-shaped and box-shaped floors respectively, designed for 30 minutes fire resistance and 7 metre spans. Specimen A consisted of two 400 mm deep x 45 mm wide LVL joists glued in a pair under a 36 mm thick x 1200 mm wide cross-banded LVL slab. The joists were fixed together in pairs to reduce the area of timber exposed to fire thus increasing the expected fire resistance of the assembly. Specimen B consisted of a box section formed from 360 mm deep x 45 mm wide LVL joists and a 45 mm thick x 300 mm wide LVL bottom flange. This box section was fully fixed to a 36 mm thick x 1200 mm wide cross-banded LVL slab, similar to Specimen A.

Specimens C and D were larger T-shaped and box-shaped floors respectively, designed for 90 minutes fire resistance and 8 metre spans. Specimen C consisted of three pairs of 450 mm deep x 90 mm wide LVL joists glued under a 108 mm thick x 1200 mm wide cross-banded LVL slab which was made up of 3 layers of 36 mm thick cross-banded LVL glued together. Specimen D consisted of two box sections formed from 300 mm deep x 90 mm wide LVL joists and 90 mm thick x 400 mm wide LVL bottom flanges. The box sections were glued and screwed to a 108 mm thick x 1200 mm wide cross-banded LVL slab composed of three separate layers glued together. All floors were simply-supported, and the glue used to produce the LVL materials was a phenolic resorcinol adhesive which produced a Type A marine bond.

Loading and Fire test Protocol

The loads were applied to the specimens for 30 minutes prior to furnace testing in accordance with AS 1530.4 (2005) and ISO 834 (1999), and were held constant throughout each test until termination. Four point bending was simulated on the floors with a spreader bar approximately 1.6 metres in width located centrally on the specimens. The applied loads for the floor specimens were calculated based on normal office loading characteristics from AS/NZS 1170.1 (2002), with a live load of 3.0 kPa and a superimposed dead load of 1.0 kPa plus the self-weight of the floors. The floors were subjected to the standard ISO 834 (1999) test fire for varying durations until runaway failure was observed and they were unloaded from the furnace for damage assessment.

Test Results

Char measurements were taken at quarter points throughout the length of the floor for each test, with the actual char depth observed to be remarkably uniform across each specimen indicating a relatively consistent level of combustion inside the furnace. The average calculated charring rates of each major surface of the floor specimens are shown in Table 1 with regards to the furnace testing duration and total burning time of each specimen. Note that there is a period of time from which the test is terminated until the test assembly can be disassembled and the test specimen extinguished, hence the total burning time is greater than the furnace testing duration.

Table 1 Calculated charring rates from furnace testing

Specimen	Test Duration (min)	Burning Time (min)	Calculated Charring Rate (mm/min)			
			Beam Sides	Beam Bottom	Slab Underside	Overall Average
A	30	36	0.69	0.83	0.69	0.74
B	41	-	-	-	-	-
C	105	113	0.66	0.86	0.84	0.79
D	105	113	0.68	0.71	0.84	0.74

The charring rates for the exposed surfaces of the floors ranged from 0.66 – 0.86 mm/min across all specimens. Charring rates for the vertical faces of the floors (sides of the beams) were all similar, ranging between 0.66 – 0.69 mm/min.

The T-shaped floors had much higher charring rates on the bottom of the beams due to the corner rounding effect where in the latter stages of burning the radii of charring on each corner of the beam intersect, compounding the vertical rate of char. This was observed in previous research on timber-concrete composite floors tested at BRANZ (O'Neill 2009). In contrast, this effect was not as pronounced for the box-shaped floors which experienced a greater relative degree of one-dimensional fire exposure, with a calculated charring rate on the underside of Specimen D of 0.71 mm/min.

The charring rate of the lightweight 36 mm thick timber slab was 0.69 mm/min in Test A, while the heavyweight 108 mm thick slab charred at 0.84 mm/min for Tests C and D. This higher rate can be attributed to the longer duration of burning where the furnace temperatures are comparably higher at this time. The temperature in the furnace was recorded as approximately 850°C at 30 minutes and reached temperatures over 1000°C after 80 minutes of exposure to the standard fire. As Specimen B was tested until failure at 41 minutes, no viable charring results could be obtained from the remaining specimen as it could not be retrieved from the furnace in adequate time. The uniformity of the charring is shown for Specimen D in Figure 2, before and after furnace testing (approximately 113 minutes burning time).

Figure 2 Underside of Specimen D before (left) and after furnace testing (right)

NUMERICAL MODELLING

Advanced numerical modelling is required when a problem is too complex to be solved by hand, and a greater understanding is required of the underlying principles and mechanisms involved in the analysis of the problem. Modelling is useful in fire engineering because it allows the investigation of parameters in the structural system while fire testing will only yield results for only one particular circumstance.

Numerical Modelling Conducted

A sequentially coupled thermo-stress analysis was conducted on each floor to determine the effects of fire on loaded floor assemblies using the software ABAQUS (2010). Firstly a two-dimensional thermal analysis was performed to track changes in the temperature profiles of the floor assemblies for the duration of the fire, and then a three-dimensional stress analysis (utilising solid continuum brick elements) was performed using the temperature profile as an input into the structural model. This procedure was used as the stress profile of a timber member is influenced by its temperature profile, but the converse is not true.

Potential Drawbacks

Sequential thermo-stress analysis of timber floor systems is difficult for many different reasons. It requires the definition of thermal, mechanical and physical properties. Mass transfer in timber members exposed to fire conditions is the fundamental process which governs many of these property changes. However, modelling any type of mass transfer is extremely difficult and time consuming; hence it is usually accounted for by taking effective values of other properties over a certain range. A review of some of the numerous models which incorporate some moisture movement is described by Janssens (2004). It highlights some of the difficulties and drawbacks of efforts in the past to model and predict charring behaviour by accounting for mass transfer, char oxidation, char contraction and modified properties. Although higher order effects such as these are important to understand, finding a method of reliably accounting for them without actually modelling the exact mechanisms taking place is difficult, and has been attempted in the past with varying degrees of success. As the thermal and structural effective properties presented in Eurocode 5 (CEN 2004) are able to model these effects well, an effective values approach is recommended for the numerical modelling of timber in fire.

Results Comparison

The ABAQUS simulations of load vs displacement data were compared with the results of experimental tests. It was found that the numerical model predicted the displacement response of the experimental floors very well, but was slightly under conservative when estimating failure times. Failure time comparisons from the numerical modelling effort and for the experimental tests conducted are shown in Table 2. Modifications to the effective material were proposed. These resulted in a closer approximation to the experiment, as shown in Figure 3.

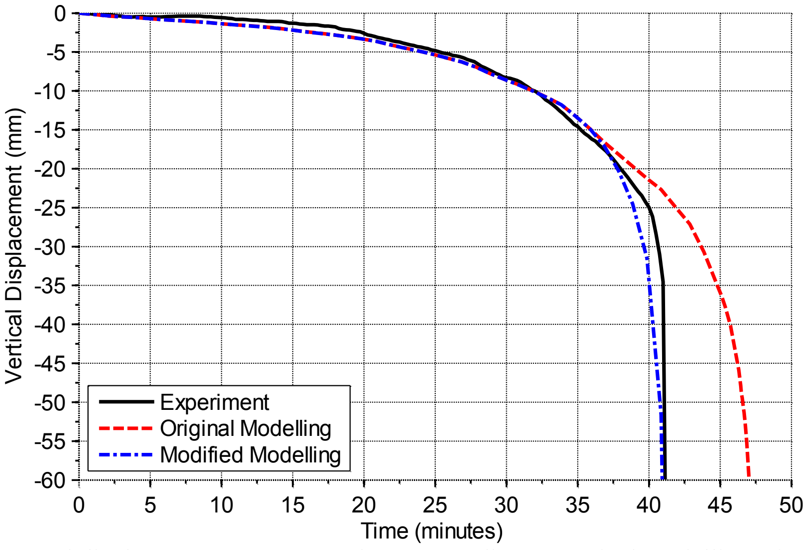

Figure 3 Load displacement response and corresponding numerical modelling of Specimen B

Table 2 Test durations and failure predictions

Specimen	Expected Failure Time from Experiment (minutes)	Failure Time from Numerical Modelling (minutes)
A	33 – 37	38
B	41	47
C	120 – 125	133
D	120 – 125	135

These modifications included varying the maximum tension strength reduction factor of the wood, based on a range of material properties data available in the literature. Sensitivity studies were conducted to determine the most influential parameters within the material model, including strength, modulus of elasticity, Poisson's ratio, and damage functions. Although the comparisons in Figure 3 highlights the importance of advanced calculations, simplified design methods are also needed for calculating the fire resistance, as a resource and time efficient method must also be available to facilitate everyday timber design calculations.

DESIGN METHOD

Simplified design methods are the backbone of current engineering practices in the modern environment. Although each structure and its expected hazards may be unique, a simplified approach and its supporting design methods allow the majority of these structures to be designed by engineers of varying skill levels while still attaining a minimum acceptable standard.

Current Practice

A number of simplified design methods exist for the prediction of timber member capacity in fire conditions, such as the reduced cross-section method or the reduced properties method. Although these methods have been developed to suit local design practices, there is consensus that charring rate methods are simpler to understand and apply as they reflect the physical changes a burning timber element undergoes. As such, this research proposes a charring rate methodology which is grounded in the basic acceptable practices from around the world. Although reduced properties methods are also available in some building codes, these methods are less intuitive, and less widely accepted and applied, hence are not investigated further in this research.

Generally accepted practice is to apply the above charring rate methods via Limit State Design or a similar means to determine the structural adequacy of a timber member or assembly. For fire conditions, short term loading durations are generally assumed, and the structural adequacy is checked under the Ultimate Limit State only. Fire design loading conditions are applied, which take into consideration the lower expected loading demand on the structure during this type of scenario. Loading factors vary between countries, however they generally consist of a gravity load factor of 1.0 and a live load factor of 0.5 or less. A full design procedure for the Australian and New Zealand design environment for timber assemblies is described by O'Neill (2013).

Failure Criteria

The standard measure of the fire resistance of an element is generally classified by three separate failure criteria, and are listed as follows:

- Stability – to prevent the structural collapse of the element,
- Integrity – to prevent the transmission of fire and smoke through the element,
- Insulation – to prevent an unacceptable amount of heat being transmitted through the element.

These criteria are generally abbreviated into a short form which is expressed in minutes as R/E/I. This represents the failure criteria fire resistances of stability, integrity and insulation respectively. This is known as the fire resistance level (FRL) of an element in Australia or fire resistance rating (FRR) in New Zealand, and has many similar abbreviations around the world.

Design Method for Structural Adequacy

The simplified method developed in this research is based on a reduced cross-section method that utilises notional charring rates to incorporate second order effects and the effect of corner rounding. This is because corner rounding often complicates what should in essence be simple hand calculations, and the impact of corner rounding is highly dependent on the exposure duration. Thus a residual section can be calculated for an entire timber section by removing the expected char layer from all exposed faces of the section, including a zero-strength layer. The charring rate also incorporates bi-linearity, as the experimental results and other studies (Gardner and Syme 1991) have shown the rate of charring decreases significantly with increasing char thickness. The proposed bi-linear method is shown in Eq. 1.

$$d_{char} = \gamma\beta \times t + kd_0 \tag{1}$$

Where d_{char} is the char depth in mm, and t is the duration of burning in minutes. The bi-linear modification factor, γ, is defined as $\gamma = 1.15$ for $t < 45$, and $\gamma = 0.90$ for $t > 45$. The notional charring rate, β, is defined as 0.70 mm/min for softwoods and 0.55 mm/min for hardwoods, and d_0 is the zero strength layer, specified as 7 mm. These values were chosen as a good approximation to the experimental results in this research, and are also representative of a wide range of currently accepted codes such as in Australia (SA 2006) and Europe (CEN 2004) which specify similar values of nominal charring rate and zero strength layers. The k factor is calculated as $k = t / 20$ for $t < 20$, and $k = 1.0$ for $t > 20$, similar to the Eurocode (CEN 2004).

Design Method for Insulation and Integrity

The above charring methods are for calculating the expected resistance of a timber member or assembly, however they generally only provide information regarding the stability (or loadbearing) criterion of fire resistance. This may be acceptable for evaluating members such as columns and beams, however when dealing with assemblies such as floors or walls which are also required to provide a separating function, the insulation and integrity criteria must also be evaluated. Guidance from the codes is limited on the matter, with none of the above outlined codes providing any information or design procedures for evaluating the integrity or insulation criteria excluding Eurocode 5 (CEN 2004). It provides guidance on the separating function of wall and floor assemblies, with an additive method which accounts for the contribution of different layers of materials, their positioning in the assembly, and their location relative to joints. It has been shown to provide a conservative calculation of the separating function of wood decking (Janssens 1997). Further modifications and improvements to this method are given in the European Guidelines (Östmann 2010).

It is usual for an upper limit to be provided in terms of the allowable maximum temperature to be reached on the non-exposed cold face of the element, however accurately estimating the thermal penetration into a wood member requires a heat transfer analysis to be conducted, and is beyond the scope of simplified calculation procedures. A simplified approach to assessing both integrity and insulation is postulated in this research by which the insulation criterion, considering an unburnt thickness of wood is evaluated. As the remaining thickness of wood is assumed to be large enough to ensure the non-exposed face of the element does not undergo a significant rise in temperature, the integrity criterion is then also conservatively assumed to be satisfied with the insulation criterion.

It is estimated that an unburnt wood layer thickness ranging from 15 – 35 mm is appropriate to use for design, based on experimental testing and guidance from the literature (Buchanan 2001). Due to the insulative properties of timber the steepness of the temperature gradient is high, such that if timber is assumed to be converted to char at 200°C it may be assumed that the temperature of the non-exposed face of the timber separating element should be below 100°C. A value of 25 mm is suggested, based on the one-dimensional thermal modelling conducted by O'Neill (2013) and validated against experimental results incorporated into Eurocode 5 (König and Walleij 1999). Using this approach, a simple effective thickness calculation can be added to any charring rate method to evaluate the separating function for wood assemblies.

Building Code Comparison

As a comparison between currently used simplified methods, calculations of char depth are made for the bi-linear method compared with a selection of regulatory codes from around the world for a number of generic fire resistance times. The results are shown in Table 3, considering the effective charring depth (including zero strength layer approximations) of an unprotected segment of softwood timber under two-dimensional fire exposure. In comparison to the other code methods, the proposed bi-linear charring rate is notably more conservative for all exposures under two hours (excluding the two hour Eurocode 5-1-2 exposure). This is to be expected as the notional charring rate for the initial 45 minutes of exposure time is very high in comparison to other codes.

Table 3 Building code char depth calculation comparison

Calculation Method	Char Depth (mm)			
	30 min	60 min	90 min	120 min
NZS 3603	20	39	59	78
AFPA Technical Report 10	26	46	64	80
AS 1720.4	27	47	67	87
Eurocode 5-1-2	28	49	70	91
Proposed Bi-Linear Method	31	53	72	90

As these methods are all rooted in empirical findings of experimental tests, it is impossible to say which is the most appropriate for design without comparing the experiments themselves. Therefore common sense dictates the most robust testing regime, coupled with the most detailed analysis should take precedence over the others. However environmental factors may have also influenced the results, and hence each method may be appropriate to its specific region thus no definitive conclusions can be drawn in this sense. What is apparent from comparing the methods is that the assumption of a zero strength layer is common, as is accounting for the influence of the density of the wood. The application of each method is seen to be similar, however the assumption of a linear or non-linear charring rate, and the absolute charring rate value used can cause large discrepancies between the results.

Experimental Comparison

In order to gain an understanding of the spread of historic experimental data on measured charring rates around the world, the results of a number of experimental investigations have been summarised in Table 4. These results are readily available in the literature, and where reported the type of test assembly and wood species classification is given (with either hardwood or softwood denoted as “S” or “H”). Some of these results have been extracted from the research review work of Friquin (2010) and O’Neill (2013). The bi-linear calculation method has been applied to each historical test dataset for comparison.

Table 4 Experimental char depth comparison

Experimental Reference Source	Assembly Type	Species	Recorded Charring Rate (mm/min)	Bi-Linear Method (mm/min)
Collier (1992)	Wall Beam	S	0.53 – 0.93 0.57 – 0.63	0.88
Frangi and Fontana (2003)	Beam Slab	S	0.67 – 0.70 0.70	0.76 – 1.04
Frangi et al. (2008)	Wall Slab	S	0.64 – 0.78 0.99	0.85 – 1.01 1.06
Gardner and Syme (1991)	Beam	S H	0.50 – 0.94 0.40 – 0.63	0.75 – 0.88 0.60 – 0.71
König and Walleij (1999)	Slab	S	0.60 – 0.70	0.79 – 0.88
Lane (2005)	Beam	S	0.72	0.99
Lau et al. (2006)*	Beam	S	0.70	1.15
O’Neill (2009, 2013)	Beam	S	0.66 – 0.86	0.76 – 0.85
Osborne et al. (2012)	Slab Wall	S	0.64 – 0.65 0.65 – 0.80	0.71 – 0.86 0.76 – 0.89
Schaffer (1967)	Slab	S H	0.50 – 0.80 0.43 – 0.57	0.90 0.73
Tsai et al. (2010)	Beam	S	0.75 – 0.94	0.88
White (1988)	Slab	S H	0.50 – 0.86 0.55 – 0.97	0.83 – 0.96 0.68 – 0.81
*Only the experiments over 20 minutes in duration were collated.				

Note that the experimental results reported in Table 4 encompass both one and two-dimensional charring behaviour which is dependent on the test and assembly type. The timber elements are exposed to standard fires, and subjected to a wide range of loading regimes. All of these factors have an influence on the charring rates recorded. It can be seen from the wide range of data sourced that the spread of measured charring rates is large, with approximate charring rates for softwoods between 0.60 – 0.80 mm/min for the test exposures of beams, slabs and walls. The results for hardwoods are on average lower, being between 0.45 – 0.65 mm/min. The experimental test times for the data listed ranged from 20 – 120 minutes.

The proposed bi-linear method overestimates many of the average charring rate values recorded in the historical test dataset. This is due to a number of factors such as exposure time, the increased initial charring rate, and the inclusion of a zero strength layer for design. This has a magnified impact on very low test exposure times such that a high level of char is calculated, and the method is conservative overall in comparison to the test dataset. Variations in the zero-strength layer were not considered during the research, however if considered, it is expected to have a greater impact on values calculated for lower exposure times.

The work conducted by Gardner and Syme (1991) found that, comparing one and two hour fire exposure, the average charring rate for softwoods decreased from 0.79 to 0.65 mm/min. For hardwoods the decrease was much lower, decreasing from 0.55 to 0.52 mm/min on average. Post-fire investigations of actual buildings have found that without the presence of accelerants or specific design flaws such as large gaps in timber assemblies, charring rate values reported in the literature for fire resistance furnace tests are representative of real fires. Babrauskas (2004) concluded that charring rates between 0.50 – 0.80 mm/min are representative of severe post-flashover room fires.

In comparison to the experimental results and failure times predicted by the numerical modelling in this research, the expected fire resistance calculated by the bi-linear method for each floor specimen is shown in Table 5. This is calculated for stability failure only, as it is expected that in practice a lightweight non-structural concrete topping or other insulating membrane would be installed atop these floors for the purposes of better acoustic, insulation and durability properties. Thus the insulation and integrity criteria are not expected to govern the fire design of these floors. The calculation method was implemented in a spreadsheet as a quasi-steady state analysis in order to iteratively solve for the expected failure time of the floors to the nearest minute. A comparison with the Eurocode 5-1-2 method is also presented for the floors tested, as this method is widely used worldwide and gave the closest calculated char values to the proposed bi-linear method.

Table 5 Experimental failure time comparison

Specimen	Expected Failure Time from Experiment (minutes)	Failure Time from Numerical Modelling (minutes)	Failure Time for the Bi-Linear Method (minutes)	Failure Time for the Eurocode Method (minutes)
A	33 – 37	38	35	40
B	41	47	41	47
C	120 – 125	133	123	122
D	120 – 125	135	124	123

It can be seen that the bi-linear method is more conservative than the results of the numerical modelling, and predicts the failure time of the experiments well, which is expected. The Eurocode 5-1-2 method gives very similar results to the proposed bi-linear method for higher exposure times, however gives more conservative values at lower exposure times. This can result in the over prediction of expected failure times of up to 20% for some of the floor assemblies tested in this research.

It should be noted that the floor assemblies tested in this research may not perform in a similar manner when compared with other major structural assemblies such as walls, beams and columns. This may affect how the calculation method performs for these other assemblies. The load level, fire type, and surface fire exposure all play a critical role in determining the actual fire resistance of a timber assembly, and these factors can differ significantly between different types of assembly.

Despite this, the condition of the floors tested in this research should be representative of a wide range of flooring systems used in reality, in terms of load levels, cross-sectional geometries and span lengths. Thus, the bi-linear charring rate reduced cross-section method is generally applicable for these types of systems, and provides an excellent starting point for estimating their performance by hand calculation methods.

Designing for Redundancy

Care must be taken when using calculation methods to ensure that they are used appropriately for their intended purpose, and that other parts of the system which may be critical to the design are not ignored. Any other elements in the system which may cause premature failure or increased burning, such as the integrity of the connections, thin portions of slab, unprotected penetrations and holes drilled into floors, openings through wall cavities exposing more timber surface area, and any surface treatment or covering which could have an adverse effect on the fire performance of the assembly. The effect of passive protection on timber assemblies should also be accounted for.

As such, a greater understanding of the global behaviour of the structure and any critical elements such as connection details must be appropriately designed for fire resistance to ensure the entire system performs as desired, and a premature failure does not occur in the event of a fire. Good construction practice is also paramount to ensuring that a structural assembly performs as intended.

CONCLUSIONS

In conclusion, this research has incrementally consisted of the experimental testing and numerical modelling of timber floor systems under fire conditions, culminating in a simplified charring method derived from the results of the research and grounded in generally accepted calculation methodologies from around the world. A bi-linear charring rate method is proposed, accounting for a zero strength layer and with provision for calculating a separating function.

As many of the new timber technologies which are becoming prevalent in our markets have not yet been properly implemented into building codes, it is becoming increasingly important to provide evidence and guidance on their expected performance in fires. This is not only to enable the correct use and implementation of these systems in the built environment, but to allow for informed and reasoned justification behind any restrictions placed on timber systems which may form the basis of modern building codes.

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