MODELLING THE FIRE PERFORMANCE OF STRUCTURAL TIMBER FLOORS

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Abstract. *This paper describes numerical modelling to predict the fire resistance of engineered timber floor systems. The floor systems under investigation are timber composite floors (various timber joist and box floor cross sections), and timber-concrete composite floors. The paper describes 3D numerical modelling of the floor systems using finite element software, carried out as a sequential thermo-mechanical analysis. Experimental testing of these floor assemblies is also being undertaken to calibrate and validate the models, with a number of full scale tests to determine the failure mechanisms for each floor type and assess fire damage to the respective system components. The final outcome of this research will be simplified design methods for calculating the fire resistance of a wide range of engineered timber floor systems.*

1 INTRODUCTION

With the advent of high performance wood materials such as glue laminated timber, laminated veneer lumber (LVL) and cross-laminated timber (CLT), timber floors are once again a viable alternative to using steel or concrete in multi-storey buildings. This raises the question of fire resistance, because timber is a combustible material. The loss of wood section due to charring, the anisotropy of the material and the detailing of connections all complicate the estimation of the fire resistance of timber floor systems. This research focuses specifically on the fire performance of different timber floor types used in multi-storey timber buildings.

1.1 Timber Composite Floors

Timber composite systems such as ribbed panel floors and hollow box floors are generally categorised as having sheathing on one or both sides which acts as part of the structural system based on the performance of the connection between sheathing and beam elements (commonly a nailed, glued or screwed connection along the beams, or some combination of glue and fasteners). Composite action achieved by the floor system must be accounted for to obtain a proper estimate of fire resistance, however composite action is not considered in the simple design methods currently available [1].

The composite joist floor currently being researched consists of LVL beams ranging from 200 mm to 600 mm deep, bound by small LVL bottom flanges and a continuous LVL slab system as the primary supporting floor panel (top flange). A schematic drawing of a typical composite floor is shown in Figure 1. Similar types of flooring systems are discussed in detail by Grant [2].
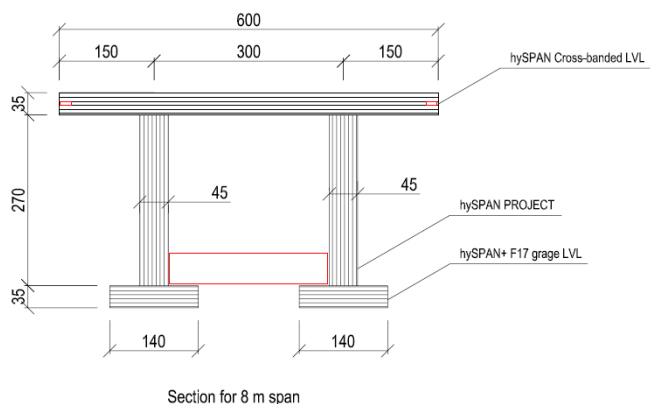
Figure 1. Timber composite joist floor system.

Typically these floors span from 5 metres to 12 metres and are designed for normal service loads in office buildings and similar multi-storey applications. When compared with a simple joist type composite floor, this configuration gives the added mechanical advantages of supporting greater loads at a higher level of stability, hence resulting in the overall reduction of the floor member sizes after geometrical optimisation. However a larger area of timber is exposed to the fire in this regard, and due to the smaller member sizes the expected unprotected fire resistance of these floors will be lower under similar loading conditions.

The composite box floor under study is identical to the joist floor in all aspects but construction geometry. The bottom flanges of the joists are made continuous between each second pair, resulting in a box type system with every second panel missing on the bottom chord, allowing for services to be installed in the gaps. The advantage of a system such as this over the previous composite floor discussed is that the surface area of timber exposed to the fire is greatly decreased, hence the expected fire performance will be greater by a simple change in geometry.

1.2 Timber Concrete Composite Floors

The concept of timber-concrete composite systems arose in Europe as a method of strengthening existing timber floor systems using a concrete slab. A summary is given by Lukaszewska *et al.* [3]. This was then applied to construction of new buildings, and is currently under investigation in many parts of the world such as the United States [4], Germany [5,6] and New Zealand [1,7]. The performance of the flooring system depends mainly on the connection between the timber beams and the concrete slab, as a very stiff connection is required to ensure that sufficient composite action is achieved, resulting in a higher ultimate strength and decreased deflections.

The fire resistance of timber-concrete composite elements is mainly influenced by the timber and the connectors [8]. Effects of the fire on the timber such as heating and reducing overall section size act to weaken both the timber section and the connection between timber and concrete. The form of connection is also important, as the integrity of the connection during the fire will be governed by its weakest element which can sometimes be difficult to predict.

Timber concrete composite floors have been researched previously at the University of Canterbury [9,10], and a full set of fire performance data is available for two full-scale tests which were undertaken as a part of that research. Due to time constraints however, an in-depth analysis of the floor system was not possible and hence a simplified design method for these floors was not developed. Part of the current research is aimed at remedying this issue, and the timber-concrete composite floors shown in Figure 2 are being investigated alongside the fully timber systems.
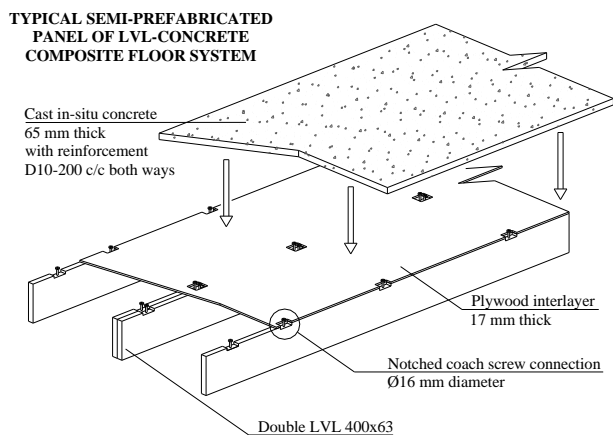
Figure 2. The timber-concrete composite floor system [9].

The type of composite floor under study is a semi-prefabricated system comprising of "M" panels that are built with LVL beams and sheathed with a thick plywood interlayer, which acts as a permanent formwork for the concrete. The plywood interlayer has holes cut into it to accommodate the notched form of connection being used between beams and the concrete slab. These panels are prefabricated off-site then transported to site and craned into position. Steel reinforcement can then be assembled and the concrete slab cast in-situ, with the floors being propped as required.

A simplified design method developed for timber-concrete composite floors [11] based on the effective cross section method from Eurocode 5 [12] gave good results when compared with large scale fire tests. Although these systems have some major differences to the one under investigation in terms of connection type, timber species and major floor element geometries, it provided an insight into methods in which the issue of fire resistance for these systems can be addressed.

2 MATERIAL PROPERTIES

2.1 Laminated Veneer Lumber

New Zealand laminated veneer lumber (LVL) consists of 3-4mm thick rotary peeled veneers of Radiata Pine glued with resorcinol adhesive. These layers have the grain orientation running in the same direction (as opposed to plywood alternating grain orientation by 90° for each layer) which gives the highest strength properties for bending and tension in one direction. Such beams can resist much greater loads and hence span longer distances compared with traditional sawn timber. The manufacturing process of LVL also allows for greater dimensional accuracy, and additives such as fire retardants can also be implanted in the veneers depending on the desired performance.

The fire behaviour of LVL has been investigated in recent years. Research by Lane [13] has looked into the ignition, charring and structural performance of LVL. In terms of the glue lines in LVL affecting the charring rates, Lane found in a number of un-instrumented char tests that there was relatively no difference between charring parallel or perpendicular to the grain. These results suggest that the presence of the glue lines do not influence the burning behaviour of the material.

Lane conducted cone calorimeter tests on LVL samples, and furnace tests on LVL members. This furnace testing consisted of subjecting LVL members to the standard ISO 834 fire [14] in a pilot furnace, and also in a full scale furnace under loaded conditions. From this research he suggested a charring rate for New Zealand manufactured Radiata Pine LVL of 0.72 mm/min under standard fire exposure. This is similar to the charring rate of 0.70mm/min for LVL in Eurocode 5 [12].

3   NUMERICAL MODELLING

Advanced numerical modelling is required when a problem becomes 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. This is often desirable to the alternative of experimental testing, as testing can be uneconomical, time and labour intensive, and only one particular set of circumstances can be investigated in each test. Furthermore when considering the modelling of floors, a numerical modelling approach allows for vast amounts of data to be calculated for many different types of floor geometries and loading conditions in an economical and efficient manner. Complex geometries and load transfer between floor components can be designed and accounted for, while very precise loading arrangements and material properties can be specified for a particular situation. This enables the user to obtain results directly proportional to the quality and quantity of the input into the software, and at a specified level of detail. It is important that the analytical method used is not pushed beyond its limits of applicability [15]. Higher order effects of fire impact on timber such as mass transfer (moisture movement), thermal creep, char cracking and drop-off can also be incorporated into the analysis, thus enabling many different influences on floor performance to be investigated at once and key factors affecting the overall performance of the floors to be isolated.

The software ABAQUS [16] was used for the numerical simulations. The approach taken in this research was stepwise, gradually introducing increased levels of detail into both the thermal and structural analyses. Initially only one-dimensional problems were considered, moving on to two-dimensional (2D) simulations and eventually graduating to three-dimensional (3D) analyses. The models were constantly compared with test results where applicable to ensure reasonable output was being achieved at each step of the analysis, and the previous models used to ensure the accuracy of the results.

The ultimate goal of this modelling was to conduct 3D sequentially coupled thermo-stress analyses to determine the effects of a fire on floor assemblies under load. This involved a thermal analysis to determine the temperature profile of the floor assemblies for the duration of modelling, and then a stress analysis 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 the temperature profile, but the converse is not true, in other words the temperature is not affected by mechanical stresses and can be computed as a separate initial step.

3.1 Thermal Modelling

For greater confidence in the results obtained, three separate numerical software suites were run in collaboration during this research focussing on defining acceptable material parameters and expected behaviour. The numerical software used in this research was ABAQUS [16], however both ANSYS [17] and SAFIR [18] have been used for verification.

The first objective of the thermal modelling was to determine the acceptable range of parameters to use in ABAQUS to appropriately model one- and two-dimensional heat transfer through timber sections. A second objective was to define an appropriate set of effective material properties comparable with experimental results found in literature, and what was achieved through modelling in similar software packages. Detailed results of this and comparisons between the three software suites are described by Werther *et al.* [19]. As a baseline for configuring the material model of timber for heat transfer in ABAQUS, the properties found in Annex B of Eurocode 5 [12] were used; specifically these were the thermal conductivity, specific heat, latent heat and density. Using these values was recommended as a way of accounting for the physical and chemical changes that occur as timber combusts, such as moisture movement, charring and shrinkage. These effective values also encompass many second order effects and allowed for simplified modelling of heat transfer through timber, while still giving a good approximation to timber behaviour in reality.

The input of thermal properties into software was implemented in two separate procedures. The first was a user defined $k\rho c$ model, where the symbols represent the thermal conductivity, density and specific heat, respectively. The specific heat is defined as the amount of energy required to change the temperature

of a material by a unit amount, in SI units this is measured in kJ/kgK. In the case of timber there is a peak in the reported values of specific heat, most commonly taken as between 99 to 120°C. This is to account for the vaporisation of water in the timber, and results in a large increase in energy required to facilitate this phase change from liquid to gas. The second procedure was the latent heat model that allows for the removal of this peak from the specific heat curve, as it accounts for the extra energy of phase change over the specified temperature range. Further validation of this work in comparison to experimental results is also discussed by Werther et al. [19].

For the 3D thermal modelling of timber floors, the temperature distribution in the cross section was computed as an uncoupled heat transfer analysis using 8 node linear solid elements, DC3D8 [16]. Depending on the floor geometry, beams are generally subjected to 3 sided exposure to the ISO834 fire as a standard temperature input into the models, and this is also applied to the underside surfaces of the floors. This was applied via surface film conditions and surface radiation to the exposed surfaces, and ambient conditions were modelled on the top of the slab. The convection coefficient and emissivity were taken from Eurocode guidance [12,21] and assumed to be 25 W/m^{2}K and 0.8, respectively. As an initial starting point for 3D thermal modelling the cross section was discretised into a 6 mm mesh, and along the length of the floor the mesh was left very coarse (greater than 10 times the cross-section mesh size). This coarseness allowed for faster computation times, however when the mesh was translated to the structural model it proved to be poor for the stress analysis. Therefore once the final floor design was chosen a more appropriate mesh size was used along the length.

3.2 Structural Modelling

The objectives of the structural modelling were twofold. Firstly, prototype modelling of different simple loading conditions on timber such as tension, compression and bending, were compared with experimental results to give confidence in the modelling techniques. The second objective was to model the timber floor systems described in this report via sequentially coupled thermo-stress analysis.

When sequentially modelling the floors in 3D the same mesh from the thermal analysis was imported into the structural model, and the element type used was an 8 node 3D linear solid element, C3D8R [16]. To consider the reduction in mechanical properties with temperature, values for the reduction in strength and modulus of elasticity were taken from the Eurocode [12]. Timber behaves in a brittle manner in tension, and exhibits elasto-plastic behaviour in compression. Currently the material model being used to characterise these stress-strain relationships for timber is a steel yield model, which means only one stress strain curve can be adopted for both compression and tension. Future research will include development of a timber material model in which different relationships for compression and tension can be defined.

3.3 Thermo-mechanical Analysis

Sequential modelling has been conducted on timber members and systems in the past however it very commonly only considers members in either tension or compression. Modelling of bending in timber is more complex than simple compression or tension, as it is three-dimensional and buckling must be considered, as well as the method of failure being properly defined and modelled. The orthotropy of the material and appropriate failure criteria must also be included.

Numerical modelling must account for redistribution of stresses to the inner region of the beam as the extreme fibres in tension approach failure. To obtain sensible results it is important to ensure that what others in the field have done can be modelled alongside the research at each stage of development, so a final three-dimensional model can be achieved with a reasonable level of certainty.

There are a number of studies which have been conducted in the past focussing on structurally modelling timber in fires. One such study is that of Fragiacomo et al. [22] which involved the experimental testing of LVL in tension in a small scale furnace, and the efforts to numerically model the tests. The tests were conducted on rectangular sections of LVL, half immersed in a furnace and loaded under a constant tension force. A sequential thermal-stress analysis was carried out in ABAQUS concentrating on modelling the experimental testing by first building a thermal profile of the timber section, then inputting this into the three-dimensional structural model considering axial forces only.

Failure was considered to occur when the elements were no longer able to properly redistribute stresses to cooler regions, hence the solution was seen as diverging and the failure time taken as the last increment in the model. The results of this modelling slightly under-predicted the temperature in the timber when compared with the experiments, but overall provided a good approximation. The work provided insight into ways in which ABAQUS can be used to model simple structural behaviour under fire conditions.

Bobacz [23] also investigated axially loaded timber members in tension and compression under fire conditions. A large portion of his research was defining an appropriate charring model based on other work. A generic thermal model was developed to predict the temperature profile throughout a cross-section of timber, and then the simulated member was structurally analysed under fire conditions in ANSYS. In terms of assessing failure, Bobacz only considered cross section analyses in which a displacement controlled strain was applied until the ultimate strength reached, and then ultimate load at this point was derived from the integration of the stresses over this cross-section. From this he proposed a stochastic method of sizing members for fire resistance based on inputs of the three major modelling sections above. At each major step the modelling was checked against the simplified methods available in literature [12], and validated against experimental testing where possible. This research was comprehensive in both defining timber properties in fires and simplified ways of thermally and structurally modelling timber, and provided an excellent point of comparison when conducting the current research.

4 EXPERIMENTAL TESTING

A portion of this research is dedicated to calibration and validation of the numerical modelling; hence full-scale testing of these floors is required.

4.1 Tests of TCC floors

Testing was conducted at the BRANZ facilities in 2009 [10] on two timber-concrete composite floors. The primary objective of the full scale testing was to investigate the failure behaviour of timber-concrete composite floors when exposed to fire, which encompassed a wide range of information that was required to be collected from different parts of the floor system. Specifically, the failure mode of the floors was an important part of this as it would identify the critical component of the floor system that governs the design for fire safety, whether it was failure in the beams, the concrete slab or the connections between the two. Other important areas of interest were the charring behaviour of the timber beams, the spalling behaviour of the concrete, the fire damage about the connections and the performance of the plywood sheathing. The test fire was the ISO 834 standard test fire [14].

Due to their combustibility, timber beams cannot be scaled down in size as their fire behaviour is dependent on the actual cross-section present. This required that the loads on the floor units be scaled up in such a way that similar stresses were induced in the load bearing members of the floor and the same bending moment at the mid-span of the floors was obtained. The design loads of the test specimens were based on a live load of 2.5 kPa and a dead load of the self-weight of the floor only, with no additional dead load. The first floor specimen tested was the 300 mm beam floor, which was tested to destruction. Failure occurred at 75 minutes under the ISO 834 design fire and applied design load. The side with notched connections (Figure 2) failed first, and the testing was terminated. The second floor was the 400 mm beam floor and is shown in Figure 3 directly after furnace testing. This test was stopped shortly after 60 minutes to assess the damage at that time and to provide insight into how the beams were charring before complete destruction.

Figure 3. Full scale testing of a timber-concrete composite floor system at BRANZ.

4.2 Charring

The initial and remaining section sizes are shown in Table 1. Measurements represented in the table were taken from intermediate regions in the beams as the char depth across the beams was very uniform along the beams based on inspection of the charred remains.

Table 1. Residual Beam Sizes After Testing.

Test Specimen	Size Before Test (WxH mm)		Size After Test (WxH mm)		Burning Time
300 mm	126	300	44	130	75
400 mm	126	400	52	255	60

The charring rate on the sides of the LVL beams in the full scale testing was found to be 0.58 mm/min on average, lower than reported values of 0.72 mm/min based on research conducted by Lane [13] on similar LVL at the BRANZ facilities. The charring rate on the underside of the beams was very high, being on average four times as large as the charring rate from either side of the beams. This was expected as the majority of this charring occurred in the latter stages of burning once the residual section had been reduced to such a size that the central area of the timber beams had increased above the initial ambient temperature, thus increasing the rate of heating and burning of the remaining section. Further work on the charring behaviour of these configurations of beams considering different fastener types and configurations is detailed by Tsai [23].

4.3 Displacement

For both floors tested the measured vertical displacement up to the point of runaway structural failure was less than 1/20 of the span (200 mm) and the rate of increase of displacement was also low (until runaway failure occurred). Some common structural requirements specify deflections of less than 1/20 of the span or a limiting rate of deflection when deflection is 1/30 of the span [24].

4.4 Tests of Timber Composite Floors

For testing of all-wood Timber Composite Floors, a beam type floor and a box type floor will be tested at the Building Research Association New Zealand (BRANZ) facilities in Wellington. Both will have pin/roller supports and a span of 4 metres parallel to the long axis of the furnace, loaded through the

centreline at two points. The first phase of this testing will be undertaken in March 2012, to be reported at the SIF 2012 conference, and the second phase in July 2012.

5   NUMERICAL RESULTS

At this stage in the research the sequential modelling of LVL beams and composite timber floors has been conducted to such a degree that viable results have been obtained for load displacement and heat transfer. Modelling the concrete slab is currently underway, however the development of an appropriate material model to accurately predict the concrete slab behaviour has not yet progressed enough for publication. The following section compares results between the beam modelling and the test results obtained during the timber-concrete composite floor tests described.

5.1 Heat Transfer

The 300 °C thermal wave at 60 minutes for the 400 mm deep beam occurred at approximately 39 mm (48 mm remaining beam width). This compared well to the experimental results presented in Table 1 of 52 mm remaining beam width, but is slightly conservative. Further comparisons of experimental results with this thermal modelling of LVL can be found in the previously mentioned study [19].

5.2 Displacement

Figure 4 shows the results obtained for the 300mm beam modelling in terms of runaway displacement failure. This is compared to the measured fire resistance time of the 300mm floor in the test, and the calculated fire resistance time of the spreadsheet method derived from this testing.
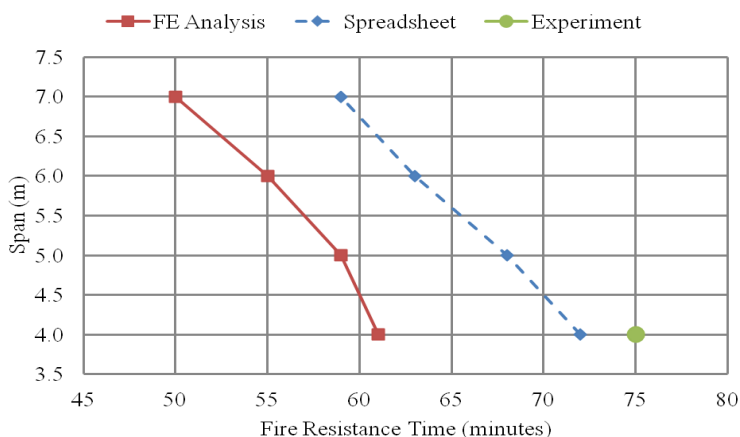

Figure 4. Modelling and experimental results for fire resistance time of 300 mm beams and floors.

The prediction of the numerical modelling for failure times of the beam shows that the model follows the same trend as the TCC floor spreadsheet calculations (based on the test data), and is on the conservative side of the data. This is expected as the TCC floors have a large degree of composite action taking place when the residual beam size becomes small, providing a longer fire resistance time.

Figure 5 shows the same results as Figure 4 but for the larger 400 mm floor. Note that the full-scale test did not go to destruction hence there is no experimental value incorporated in this plot. As before the numerical modelling prediction follows a similar trend to the calculated floor resistance times, and it is expected that once concrete slab behaviour is incorporated into the model the curves will sit closer together.
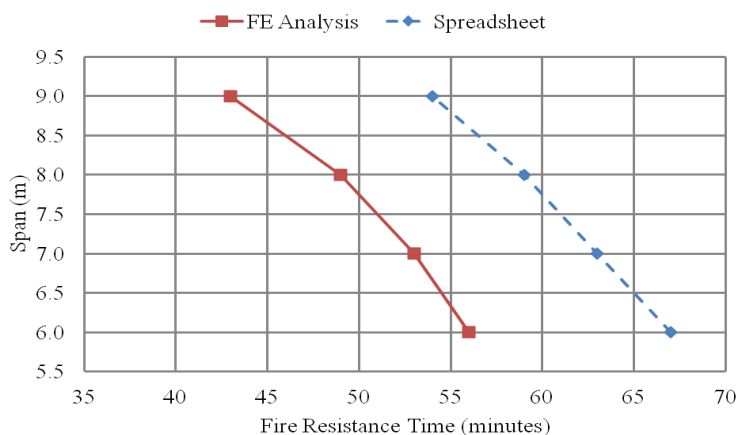
Figure 5. Modelling results for fire resistance time of 400 mm beams and floors.

6 CONCLUSIONS

This paper details the research being conducted to sequentially model timber composite floors under fire exposure. Appropriate thermal properties have been defined for the timber, verified against experimental results, allowing 3D thermal modelling to be conducted and temperature profiles of timber cross sections to be determined. Sequential thermo-stress analyses have been conducted for LVL beams and compared to experimental data from furnace tests. It was found that at this stage in the modelling the prediction of fire resistance by displacement compares well to the experimental results.

As this research is a work in progress, there remains a portion of work yet to be completed. In terms of numerical modelling, the development of more appropriate material models for timber and concrete are required to incorporate the desired mechanical properties necessary for the advanced floor analysis. Upcoming full scale furnace tests of both timber joist and box floors are also being conducted in 2012. The results of these tests will be used to validate the results obtained in the numerical modelling.

The end goal of this research is the development of simplified design methods based on the numerical modelling and experimental testing, such that the fire resistance of composite timber floor assemblies can be quickly calculated for a range of floor geometries, loading conditions and material types.

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