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MODELLING PREFABRICATED TIMBER FLOORS IN FIRE

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ABSTRACT: Current regulations on the use of structural timber in large multi-storey buildings can be restrictive due to a perceived higher level of risk with regards to fire safety. This research investigates the fire performance of unprotected timber floors for use in these types of buildings, involving both modelling and experimental testing. To fully characterise the behaviour of composite timber floor systems in fires, 3D numerical modelling was performed using finite element software. In order to validate the numerical results, full scale furnace testing of the floors was undertaken at the Building Research Association of New Zealand. The final goal of this research is to develop simplified design models to reliably predict the expected fire resistance of these floors for different floor geometries, spans, materials and loading conditions.

KEYWORDS: Timber floors, Fire exposure, Modelling, Furnace testing, Laminated veneer lumber

1 INTRODUCTION

Although timber floor systems have provided the basis for flooring needs for centuries, the development of the skyscraper with steel and concrete floor systems has made traditional timber floor systems somewhat obsolete. However high performance wood materials such as glue laminated timber and laminated veneer lumber have made timber floors a viable alternative. This raises the question of the performance of timber floors in fires. The non-combustible materials of steel and concrete can be relatively simple to predict and design for. As timber is a combustible material the situation becomes more complex, as the loss of wood section due to charring, the anisotropy of the material and the detailing of connections all serve to complicate the estimation of the fire resistance of timber floor systems.

The widespread use of structural timber in tall buildings is inhibited because timber is a combustible material and commonly perceived to behave poorly in fires. In order to facilitate the implementation of timber products into the New Zealand and Australian markets, the issue of fire resistance must be addressed. This research focuses specifically on the fire performance of different types of prefabricated timber floors used in multi-storey buildings.

2 TIMBER COMPOSITE FLOORS

The floor systems under investigation are fully timber composite systems constructed from laminated veneer lumber (LVL). The specific types of modular system are a beam type design and a box type design, typically spanning from 4 to 12 metres and designed for general office or accommodation occupancies.

2.1 BEAM TYPE FLOORS

Figure 1 shows a cross section of a typical beam type floor system. These floor systems generally consist of LVL beams ranging from 200 mm to 600 mm deep of varying widths, bound by LVL bottom flanges and a continuous LVL slab system as the primary supporting floor panel. This panel is usually cross-banded LVL, in which a number of veneers are oriented perpendicular to the primary span direction of the floor to increase panel stability and the strength in the perpendicular direction.

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Similar types of system as described above are discussed in detail by Grant [1].

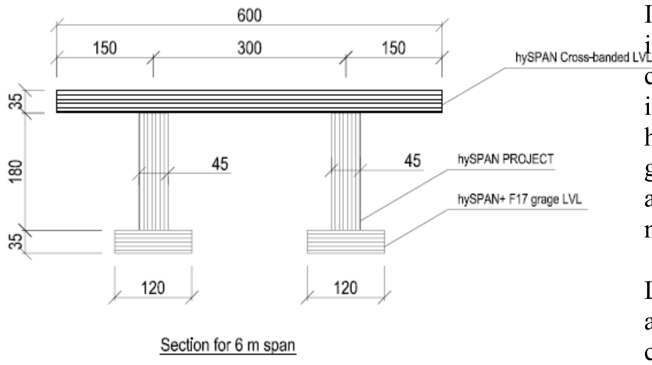

Figure 1: *Cross Section of a prefabricated LVL Floor*

2.2 BOX TYPE FLOORS

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.

The composite action achieved by both of these types of floor systems must be accounted for to obtain a proper estimate of the fire resistance, however composite action is not considered in the simple design methods currently available [2]. Therefore advanced numerical modelling is required to fully characterise the behaviour of the composite system under load in fire conditions.

2.3 MATERIAL PROPERTIES

New Zealand LVL consists of 3-4 mm thick rotary peeled veneers of Radiata Pine glued with resorcinol adhesive. Standard LVL has grain orientation all running in the same direction (as opposed to plywood which has alternating layers rotated by 90°) 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. Cross-banded LVL has a few veneers with the grain rotated by 90°. The manufacturing process of LVL allows for greater dimensional accuracy than in normal sawn timber.

The fire behaviour of LVL has been investigated in recent years. Research by Lane [3] 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 (not considering the end grain performance).

In terms of connection detail, the floors under investigation are considered to have a fully glued and continuous connection between structural members. This is a very stiff type of connection, hence it achieves a high level of composite action [4], and the resorcinol glue used exhibits good fire performance. For this reason any delamination effects of the LVL due to heating are not considered in the research.

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 [5] 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 0.70 mm/min for LVL in Eurocode 5 [6].

3 NUMERICAL MODELLING

Numerical modelling is required when a problem becomes too complex to be solved by hand, and a greater understanding is needed of the underlying principles and mechanisms. Modelling is used as a viable alternative to experimental testing, as this is usually 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 desired level of detail. However, it is important that the analytical method used is not pushed beyond its limits of applicability [7].

Many factors serve to complicate the analysis of timber structures in fire, as it undergoes an increase in temperature from ambient state to pyrolysis (thermally decomposing from a solid to a combustible gas in the case of timber). As this process occurs, the physical, mechanical and thermal properties of the timber change with time. Timber loses stiffness and strength as it is initially heated, then undergoes an increase in stiffness and strength as it dries. Strength and stiffness reduce again after the temperature increases beyond a certain threshold until the complete loss of stiffness and strength when the wood turns to char. The migration of moisture away from the heated zones affects the strength of timber, but also serves to reduce the burning rate with an increasing effect as the section size decreases. The formation of a char layer further acts to insulate virgin timber from fire with an increasing effect as the char layer increases in thickness. In addition to heat and mass transfer within the timber, other higher order effects may also be considered such as the cracking of the char layer, which increases transfer of heat into the timber section, and char contraction (shrinking of the layer). The thermal properties of timber also change with respect to temperature, most notably thermal conductivity and specific heat. The physical composition of LVL may further complicate the situation, as properties of adhesives and combined effects of layers of glue and timber and their orientation may also have an effect on the burning behaviour at the end grain. As LVL is an anisotropic material, the structural properties change depending on the orientation of the grain.

In order to fully characterise the behaviour of timber floors under load in fire conditions, computational modelling is required. This is conducted in a two-step process, involving the thermal and mechanical analyses of the system to be carried out separately. Firstly, the temperature distribution within the member is calculated to allow the residual cross section to be estimated. The temperature profile of the member is then determined using models calibrated to experimental results. A thermo-mechanical analysis can then be conducted using the previously calculated temperature profile as input into the structural model. In this research the finite element software suite used to carry out this analysis was ABAQUS [8].

3.1 THERMAL MODEL

In order to account for changes in thermal properties and other higher order effects discussed above, an acceptable range of parameters to use in ABAQUS to appropriately model one- and two-dimensional heat transfer through timber sections was determined. Subsequently an appropriate set of effective material properties were defined and compared with experimental results found in literature, and what was achieved through modelling in similar software packages, SAFIR [9] and ANSYS [10]. Detailed results of this and comparisons between the three software suites are described by Werter et al. [11]. As a baseline for configuring the material model of timber for heat transfer in ABAQUS, the properties found in Annex B of Eurocode 5 [6] 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. 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 peak accounts for the vaporisation of water in the timber, and results in a large increase in energy required to facilitate the phase change from liquid to gas. A latent heat approach was taken to account for the extra energy of the phase change over the specified temperature range, and was validated against experimental data [11].

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 [8]. The underside of the beams and floor panels were assumed to be completely unprotected and exposed to the ISO834 [5] fire as the temperature input into the models. This was applied using surface film conditions and surface radiation to the exposed surfaces, and ambient conditions were modelled on the top of the slabs. The convection coefficient and emissivity were taken from Eurocode guidance [6,12] and assumed to be 25 W/m^2K and 0.8, respectively. The cross section was divided into a 5 mm mesh, and along the length of the floor the mesh was left much coarser (between 50 and 100 mm depending on the problem size). Extruded cuts through the cross section were used to take advantage of the multiple axes of symmetry along the length and across the width of the floor, thus reducing the problem size and run times significantly.

3.2 STRUCTURAL MODEL

When sequentially modelling the floors in 3D the same mesh from the thermal analysis was imported into the structural model (as a general requirement of the analysis), and the element type used was an 8 node 3D linear solid element, C3D8R [8]. To consider the reduction in mechanical properties with temperature, values for the reduction in strength and modulus of elasticity were taken from the Eurocode [6]. 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. It is planned that the future research will include the development of a timber material model in which different relationships for compression and tension can be defined.

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. This type of modelling must account for redistribution of stresses to the inner region of the beam as the extreme fibres in tension approach failure. To obtain reliable 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. For this reason, a number of modelling checks have been made simulating what is available in the literature.

There are a number of studies which have been conducted in the past focussing on structurally modelling timber in fires. Fragiacomo et al. [13] conducted experimental testing of LVL in tension in a small scale furnace, and then made 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. 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. Although only axial forces were considered in the modelling, the work provided insight into ways in which ABAQUS can be used to model simple structural behaviour under fire conditions.

Bobacz [14] 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. 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 [6], and validated against experimental testing where possible.

4 EXPERIMENTAL TESTING

Any numerical modelling requires some form of validation to ensure its accuracy with real life occurrences. Experimental testing is used to validate the numerical modelling, with full scale tests for each major floor type.

4.1 TESTING FACILITIES

This testing and specimen construction was undertaken at the Building Research Association New Zealand (BRANZ) facility which houses a 4 metre long by 3 metre wide interchangeable floor and wall furnace. A recent furnace test on a timber composite floor at this facility is shown in Figure 2. The furnace is powered by diesel fuel. However, modifications are underway to convert this system to gas, and upgrade the loading dock to allow a walkway around the top of the furnace. The second planned series of tests in this research will be conducted on composite timber floors once this upgrading has been completed.

Figure 2: *Furnace test of a timber composite floor at the BRANZ facilities*

4.2 SPECIMEN DETAILS

The two floor specimens were constructed using LVL manufactured at Nelson Pine Industries and had a published bending stiffness of 11 GPa. All structural joints in the floor were glued using a resorcinol adhesive.

Both beam and box type LVL floor systems were tested in accordance with ISO 834 [5] and [15]. The load was applied for 30 minutes prior to furnace testing, and displacements were measured during this time, enabling a double check of the loads applied.

As seen in Figure 3 the specimens were each constructed on top of a loading frame, and this frame was lifted atop the furnace for testing. The total floor lengths were 4.4 m, and roller end supports were fabricated from steel on-site and located 100 mm in from the beam ends, thus reducing the total span of the floors over the furnace to 4.2 m. A lightweight concrete hebel block perimeter wall was constructed to enclose the top of the furnace, also shown in Figure 3.

Figure 3: *Beam type floor on the loading frame*

The floors were designed for 7 m spans in normal office loading conditions to be representative of a common floor size to be used in the industry. With simple charring rate calculations they were expected to withstand approximately 30 minutes of fire exposure unprotected. The beam floor had a 90 mm wide and 400 mm deep joist. In this case two 45 mm wide joists were glued together, however previous testing has shown this acts as a single joist [16]. The box floor consisted of two 45 mm wide joists also 400 mm deep, and a bottom flange which was 45 mm thick and 300 mm wide. The webs and bottom flange were standard LVL with grain running parallel to the span to achieve the highest strength bending behaviour possible. The top panel of both floors was 36 mm thick cross-banded LVL, with the majority of veneers running parallel to the floor span. The width of each floor panel was 1200 mm, and the openings either side of the floors were closed in with layers of fire resistant gypsum plasterboard. These were fixed on the outer edges to the block wall, and on the inner edges to the top of the floor panel, free to follow the deflection during testing. This was paramount as the furnace pressure must be strictly controlled at all times and any gaps or openings in the construction can lead to the test ending prematurely. Kaowool (mineral wool fibre) was used to seal all small openings and provide gap-filling to reduce any leakage. A layer of gypsum plasterboard was also fixed to the top of the timber floor panel to mitigate any smoking or burn through of the panel itself in the latter stages of the test.

4.3 INSTRUMENTATION

Thermocouples were installed on the top surface of the panels to measure the increase in temperature and check for a possible insulation failure. These were placed at quarter points across the top of the panel at the mid-span of the floor, under the gypsum plasterboard. Another set of thermocouples was installed on the floor at roughly a quarter of the span, with no plasterboard covering, to investigate any differences that may have arisen between insulating of the top of the thermocouples and leaving them exposed to the open air. Thermocouples were also installed inside the cavity in the box floor to measure the increase in temperature of the cavity. The reasoning behind this was to better understand the increase in temperature in exposed timber box cavities. For example, post-tensioned timber systems rely on accurate approximations of cavity temperatures to predict the tendon temperatures [17].

The load was applied via a hydraulic ram attached to the A-frame shown in Figure 2, and two loading points directly across the centreline of the floor span, spaced at 1.5 m across the centre of the floors. This arrangement can be seen in Figure 4. As the impact of fire cannot be scaled down by conventional means when compared to earthquake or wind forces, load scaling was necessary to ensure similar forces were applied to the shortened test floors as would be experienced under normal operating conditions. As the floors were designed for a 7 m span under generic office loads (3.0 kPa live load and 1.0 kPa superimposed dead load), the actual loads applied on the test specimens were scaled up to achieve the same bending moment at the midspan of the floors. This disproportionately increased the shear forces in the floors.

Figure 4: *Loading arrangement on the floors*

Two potentiometers were installed at the midspan of the floors on either side of the loading apparatus to measure the vertical displacement of the centre point of the floors.

5 EXPERIMENTAL RESULTS

5.1 OBSERVATIONS

The first floor tested was the beam floor which lasted slightly over 30 minutes. The remaining floor section is shown in Figure 5 where it is being lifted off the furnace.

Figure 5: *The underside of the beam floor directly after furnace testing*

The failure mode was a premature failure when the extreme edge of the top flange burned through near one of the loading points, forcing the test to be stopped early. This failure was due to the 600mm long cantilever edge of the top flange deflecting excessively when exposed to fire on the underside, creating an opening for increased burning at this point. This was not representative of the expected failure mode of an actual floor as the entire top panel would be continuous between modular floor units. To ensure that this was not repeated in the box floor test, stiffening ribs were attached to the top flange of the floor panel to ensure a more rigid behaviour was exhibited in the panel, more representative of an actual floor in a real building.

The A-frame was fixed to the furnace itself, hence it was required to be removed first after testing, and then the floor specimen could be lifted from the top of the furnace. When considering the combustibility of timber this was not ideal as it is desirable to extinguish the fire immediately after testing if an accurate assessment of charring damage is to be considered. However this extra time was recorded and considered in the charring rate calculations in 5.2.

The box beam test did not end until the floor began to displace beyond the acceptable limits [18] at 42 minutes. The furnace was immediately shut off and the load was removed slowly. However due to the above issue with the A-frame, the time lag between removing the frame and lifting the specimen meant that the box beam had charred so much that it failed under its own weight and collapsed into the furnace. At this time it was observed that the floor had hinged at the midspan between the loading supports, where the largest bending moment was present. The likely cause of failure was the reduction in cross section due to charring, but more specifically it may have been the corner-rounding charring that forced the failure of the floor. Once the residual section of the box beam reduced down to such a size that separation could occur on the corners between the webs and the bottom flange, the moment and shear capacity of the remaining section would be greatly diminished, causing a localised failure at the point of maximum bending moment.

5.2 CHARRING

The calculated average charring rates for the beam floor are shown in Table 1. Measurements were taken at 5 intermediate regions across the floor and the char depth was found to be extremely uniform. As the box floor fell into the furnace no charring data could be obtained for that test.

***Table 1:** Calculated charring rates for the beam floor*

Floor Part	Charring Rate (mm/min)
Beam Sides	0.72
Beam Bottom	0.68
Panel	0.75
Overall	0.72

The overall charring rate of 0.72 mm/min of the floor coincides well with values obtained in similar testing [3] and those found in guidelines [6]. Figure 6 shows a cut of the middle cross section of the beam after testing.

The residual section was approximately 35-36 mm wide and 374 mm deep, hence approximately 36% of the original cross sectional area was remaining. Due to slightly uneven combustion within the furnace it can be seen the beam is slightly bowed. This influence, however, would have no significant adverse impact on the structural performance of the floor.

***Figure 6:** Residual section of the beam floor after 31 minutes fire exposure (7 minutes additional charring)*

5.3 VERTICAL DISPLACEMENT

The average of the displacement readings from the two potentiometers on top of the beam and box floors are shown in Figure 7. The load ratios are 0.14 for the beam floor and 0.08 for the box floor.

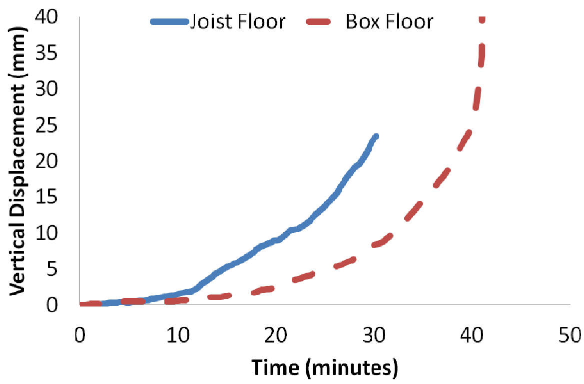

***Figure 7:** Floor displacement results*

It can be seen from the results that the vertical displacement of both floors is relatively constant over the duration of the fire testing, with a much stiffer response from the box beam floor to the load. This was expected as the load ratio was lower for this floor. The beam floor test was stopped after 30 minutes, however it can be seen from the graph and intimated from the residual section size that the floor was beginning to reach its ultimate capacity and failure was likely to have occurred within approximately 5 minutes. The box floor was tested to destruction and it can be seen that runaway failure occurred at 42 minutes in the test.

5.4 TIMBER PANEL TEMPERATURES

The temperatures for the top of the beam floor are shown in Figure 8.

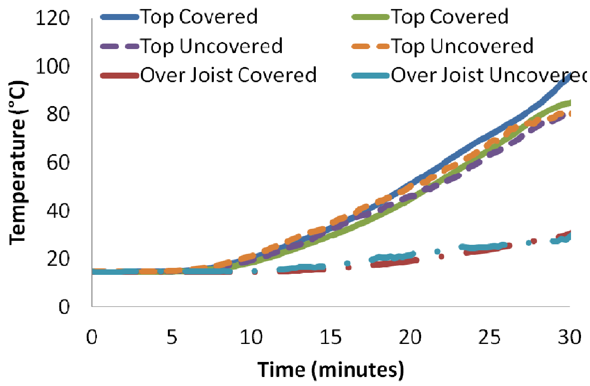

***Figure 8:** Thermocouple results for the beam floor*

It can be seen from the results that the covered and uncovered thermocouples follow very similar trends. The only discrepancies between the results were that one side of the furnace was recorded to be slightly hotter, and the uncovered thermocouples had very scattered temperature readings. This was expected as they were exposed to the open air and humidity of the surrounding environment, whereas the covered thermocouples had a very smooth temperature increase in comparison due to the insulative plasterboard above. The bottom two curves were measuring the temperature over the top of the beam, and as expected these readings were much lower than the readings from over the panel.

It can be seen that after 30 minutes the maximum temperature of the top of the panel reached 100 °C, which in general would meet most insulative criteria requirements [18]. Figure 9 shows the thermocouple readings for the box floor test.

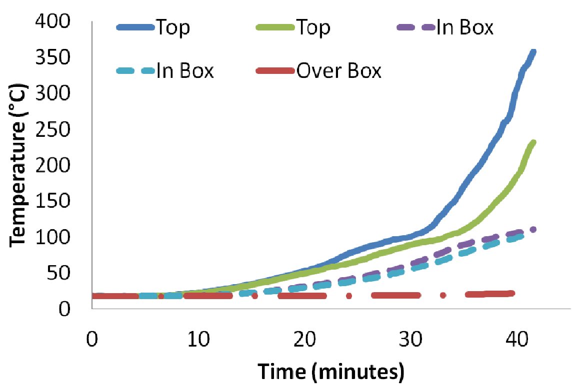

***Figure 9:** Thermocouple results for the box floor*

The panel temperatures for the box floor test are similar to those of the beam floor at 30 minutes. Due to the geometry of the floor, the interior centreline temperature of the panel over the box records almost no increase in temperature during the testing. The differences in temperature on the sides of the furnace are more pronounced in these results as the test runs for a longer period of time. A sharp increase in panel temperature is recorded around 32-35 minutes, which indicates that the temperature gradient through the timber is increasing and only a small section of timber remains. This was also seen in the char damage recorded for the beam floor test.

The temperatures in the cavity reach approximately 70 °C at 30 minutes, and 100 °C at 40 minutes. The increase is relatively constant and in the case of pre-stressing tendons or other services such as pipes or wires it shows that these would not begin to lose their own integrity for at least 30 minutes or more in similar sized box beams.

6 MODELLING AND EXPERIMENTAL COMPARISONS

As previously discussed, the current structural model has been developed to such a degree that not all behaviours of timber have been incorporated at this stage. However output from the current model is compared with the displacement measurements obtained during the furnace testing in 6.1.

Thermal modelling and verification for this research will not be discussed for this furnace testing as it has been comprehensively verified with other experimental results in another study [11].

6.1 VERTICAL DISPLACEMENT

Figure 10 shows a comparison between the experimental testing and the output of the numerical model for the beam floor.

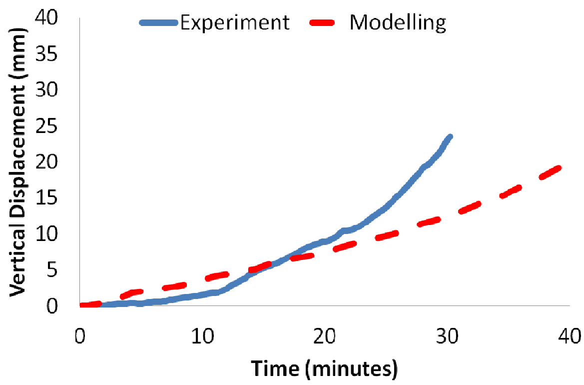

***Figure 10:** Experimental and modelling comparisons for the beam floor*

The modelling prediction shows a much stiffer response which is most likely due to the limitations of the material model used. Accounting for separate stress-strain relationships and their differing reduction factors with regard to temperature may allow for a closer fit to the experimental results in the latter stages of analysis. The assumed Poisson's ratio will also have an impact on the output, as plasticity of the material at higher deformations should be taken into account and the compressibility of the material will have a large impact on the deformation response in the model.

The results of the box beam are compared with the numerical modelling output in Figure 11.

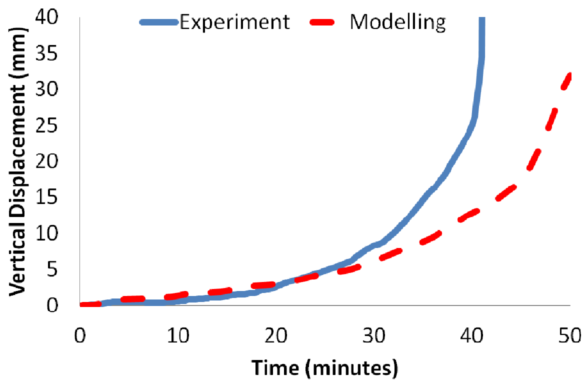

Figure 11: *Experimental and modelling comparisons for the box floor*

The modelling prediction is much closer in the earlier stages of burning, but as seen in Figure 10 the response is over predicting the stiffness of the floors in the latter stages of burning.

6.2 SIMPLIFIED DESIGN METHODS

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. More importantly, this research is a study into the applicability and use of numerical modelling to fulfil this task, and investigates the degree to which it is required.

Two more full scale fire tests are planned for July-August 2012 in which two similar composite timber floor assemblies will be tested for larger spans and higher loads, aimed at approximately 90 minutes fire exposure. The data provided from these tests will allow for validation of the numerical modelling over a broader range of fire exposures and assembly sizes, and hence expand the applicability of the design methods.

7 CONCLUSIONS

Two full-scale timber composite floor systems were fire tested in a full-scale furnace. The reduction in section size of the timber sections due to charring governed the failure of the floors. The charring rate of the LVL was found to be 0.72 mm/min on average. The displacement results obtained during the furnace testing was compared with the output of the numerical model currently under development, and the results are relatively comparable at this stage. More work is needed to develop the numerical modelling to better predict actual floor performance in fires.

The end goal of this research is the development of simplified design methods 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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