Fire performance of metal-free timber connections

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Abstract (200 words)

The fire performance of heavy timber frame structures is often limited by the poor fire performance of its connections. Conventional timber connections, dowelled or toothed plate connections typically use steel as a connector material. In a fire, the steel parts rapidly conduct heat into the timber, leading to reduced fire performance. Replacing metallic connectors with alternative non-metallic, low thermal conductivity connector materials can, therefore, lead to improved connection performance in fire. This paper presents an experimental study into the fire performance of metal-free timber connections comprising a hot-pressed plywood flitch plate and glass fibre reinforced polymer dowels. The thermal behaviour of the connections at elevated temperatures is studied using a standard *Cone Calorimeter* apparatus and a novel *Heat Transfer Rate Inducing System* (H-TRIS). The latter is a fire testing system developed at the *University of Edinburgh*. The mechanical behaviour of the connection during severe heating was also studied using an environmental chamber at temperatures up to 610°C. The results demonstrate that heat transfer in the non-metallic connections is governed by the thermal properties of the timber, resulting in significant enhancements in connection fire performance.

Keywords (chosen from the ICE Publishing list)

Fire engineering; Timber structures; Composite Materials.

1. Introduction

The growing use of engineered timber structures for the design of relatively high rise buildings (more than five storeys high) presents fundamental challenges for structural fire-safe design (Asseva et al., 2014). Specifically, heavy timber, referring to structural timber elements of large dimension (generally above 80 mm), is now widely used in commercial and industrial buildings, as beams, columns or members of trusses (Ostman *et al.,* 2010). It has become generally accepted that heavy timber performs well during and after fire (Buchanan, 2002), as the outer, charred, material becomes a natural insulator for the structural element. However, the fire behaviour of the connections often limits the fire performance of heavy timber structural systems.

During the past couple of decades, numerous research projects have aimed at identifying the fire risks and hazards associated with technological innovations in the use of timber in high rise buildings (Gerard *et al.*, 2013). For example, in recent years, research findings have shown that the fire performance of heavy timber frame structures (e.g. post and beam structures) generally relies on the protection of the steel connectors. Additionally, encapsulation of steel connections with fire barriers is neither cost-effective, nor efficient for construction, nor aesthetically pleasing. Gerard *et al.*, (2013) pointed out that there is a need for heavy timber connections that do not require fire barriers to achieve a good fire performance, in order to reduce the costs and improve the aesthetics and construction efficiency.

A comparatively low fire resistance is a general feature of traditional timber connections containing metal. The fire resistance (*i.e.* time to failure in a standard fire resistance test) of connections with exposed metallic parts exceeds 20 minutes only in exceptional cases (Carling, 1989). A fire resistance as low as 5 minutes has been reported by Leicester *et al.* (1979) for toothed plate connections. Metallic parts conduct heat rapidly into connections, where the mechanical stresses are highest (Buchanan, 2002), and soften the wood. Hence non-metallic, inflammable connectors made out of materials with lower thermal diffusivity could enhance the fire resistance of connections in timber structures. This paper presents an alternative construction technique to the use of metallic connections in ‘heavy timber’ structures (e.g. post and beam structures and roof trusses), that does not require encapsulation or other passive fire protection.

Previous research has shown the potential use of alternative materials for replacing steel in timber connections. Drake (1998) showed that glass fibre reinforced polymers (GFRPs) are suitable materials for shear dowels, and Thomson (2010) proved that densified veneer wood (DVW) is a suitable flitch plate material. For this combination of materials Thomson showed that reduced fastener spacing and end distances can lead to connections of equal capacity to similar

sized metallic connections. This type of connection is thus a viable alternative to traditional dowel type connections. However, its fire resistance has not yet been adequately studied.
This paper presents an experimental study of the fire performance of a new type of timber connection with a densified veneer wood flitch plate and glass fibre reinforced polymer dowels (Figure 1). The influence of an intumescent layer, intended to protect the flitch plate, is also investigated.

Previous studies (Pedersen 2002, Thomson, 2010) on non-metallic timber connections showed advantages regarding assembly and dimensional tolerances. Cutting the DVW flitch plate can be done using a timber saw and does not required pre-manufacturing and drilling the densified veneer wood plates can be done using regular timber drill bits (Thomson, 2010). In contrast with metallic connections, the holes can easily be drilled *in situ* through the whole connection (including timber members and the flitch plate). Small hole clearances (i.e. the void between the fastener and the timber) can be achieved as the dowel can be positioned immediately after a hole is drilled through the constituents of the connections. This positively affects the initial stiffness of the connection (Leijten *et al.* 2006). Furthermore, due to the possibility of *in situ* assembly, the connection has high dimensional tolerance compared to connections that require pre-fabrication (Thomson, 2010).

Brandon *et al.* (2013) showed that not every glass fibre reinforced polymer matrix would result in a fire resistant dowel, because some polymers soften at relatively low temperatures. Bank (2006) reported that phenolic resins have high glass transition temperatures (i.e. the temperature that indicates drastic reductions in mechanical properties) between 220 and 250°C and release water during combustion. Therefore, pultruded GFRP manufactured using phenolic resin is potentially advantageous for making timber connections with increased fire-resistance.

Carling (1989), Buchanan (2002), and Peng (2009) have all presented overviews of the fire behaviour of timber connections. More recently, Frangi *et al.* (2010), and Palma *et al.* (2014) have presented experimental work on metallic mechanical timber connections in fire testing furnaces. The limited available research studies in this area have previously focused on the fire behaviour of conventional steel timber connections in standard (cellulosic) fires. However, non-standard fire tests (i.e. any fire test other than the standard fire resistance test, also known as the standard furnace test used worldwide for the regulatory fire safety approval of structural elements) at a small scale can often generate design and model input data for predictions regarding real fires and standard fires (Östman and Tsantaridis, 1994; Bisby *et al.* 2013; Naughton *et al.* 2014;). For instance, Moss et al. (2009) have presented a series of non-standard fire tests of metallic connections that led to conclusions similar to comparable studies using standard fire testing furnaces.

Standard fire tests performed in fire testing furnaces have been the basis of structural fire safety assessment for many decades (Bisby et al., 2013). At the turn of the 20th Century, Sachs (1903) presented a set of suggested standards for a fire resistance test which proposed the use of an essentially arbitrary *"fierce"* fire represented by a minimum temperature from which the standard time-temperature curve followed in 1917*.* Fundamentally unchanged since its conception, the fire resistance test (*i.e.* furnace test) has raised the concern of numerous researchers and practitioners (e.g. Harmathy and Lie, 1970; Law, 1981). Harmathy and Lie (1970) stated that that the amount of energy (or fuel) necessary to perform a fire test is material dependent, thus does not give a rational comparison between elements made of different materials (e.g. concrete, steel, timber). Gottfried et al. (2010) stated, based on a review of fire tests, that due to inhomogeneity the temperature differences generally are in the order of hundreds of degrees Celsius. They concluded that this could lead to a significant difference in time to failure than in the generally assumed homogeneous conditions. Consistency between furnaces at different laboratories also remains questionable, since the heat flux to which the specimens are subjected depends on the furnace lining materials and geometry, which varies amongst facilities (Law et al., 2011).

Most of the current knowledge on the performance of structural timber in fire is based on tests carried out in standard furnace testing facilities, controlled to follow a standard time-temperature exposure (Ostman et al. 2010). In modern furnace tests, rather than seeking the understanding of full-frame structural fire behaviour, the standard furnace test seeks to gauge the structural fire performance based on load bearing capacity of an isolated structural element under a standard fire (i.e. time-temperature curve) (Bisby et al., 2013). This neglects the potential influence of full structural fire behaviour and the potential hazard given by real fire scenarios, not necessarily the standard fire. A further concern is that, because most furnace tests are executed with the sole objective of demonstrating compliance (i.e. regulatory approval) with a prescribed required minimum time-to-failure (e.g. 30, 60, 90 minutes), most tests are halted immediately after the required fire resistance time is achieved (Maluk, 2014). Only very few, typically research-oriented, tests continue with the tests up until actual failure of the specimen is observed; doing so in a larger proportion of fire tests could potentially lead to a much better understanding of the actual failure modes of structural elements tested. However, at present there is no obvious incentive for tests to continue any longer than is strictly required to demonstrate compliance to achieve a fire resistance rating, as required by the regulatory authorities having jurisdiction.

Within the scope of the work described here, small and medium scale specimens were tested by controlling the incident heat flux (i.e. imposed thermal energy dominated by radiation), or within an accurately controlled environmental chamber dominated by convection.

2. Experimental study

Three testing methodologies were used to determine the thermal characteristics and mechanical performance of non-metallic connections at high temperature. These are:

- loaded tests in an environmental chamber;
- unloaded tests with constant incident heat flux; and
- unloaded tests with varying incident heat flux (to simulate a furnace test).

The materials used were consistent from test to test, with specimens consisting of:

- Kerto-S Laminated Veneer Lumber (LVL);
- Phenol F4010 reinforced with E-Glass G016X as a dowel material;
- non-impregnated cross laminated DVW with an average density of 1308 kg/m^3 as a flitch plate material; and
- black mild steel (only in metallic dowelled specimens).

The dimensions and configurations of the tested specimens are defined in the following sections. All specimens were conditioned at 60% relative humidity for at least 2 months prior to testing.

2.1 Mechanical tests in an environmental chamber

Figure 2 shows the test setup of tensile tests of two single dowelled flitch plate connections, that were performed in an environmental chamber. The ports at the top and bottom of the environmental chamber were sealed with insulation boards prior to testing. Optical assessment of the specimens and their failure modes was performed through a small window in the environmental chamber's door. 25 mm thick ceramic fibre board was positioned at the top and bottom of the specimen to reduce the heat flow through the specimen ends, replicating the real thermal boundary condition. The fibre board replaces the opposing beam in a splice connection. If the heat flow through the ceramic board is close to zero, it functions as a symmetry plane, which is present in a real splice connection. Aluminium foil and 2 layers of ceramic paper were used to protect the flitch plate from breaking inside the two loading ports of the chamber.

Mechanically loaded tests were performed in the environmental chamber at temperatures up to 610°C, which was the maximum possible temperature attained by the environmental chamber. Timber chars at approximately 300°C (Buchanan, 2002) and phenolic resins have glass transition temperatures ranging from 220°C to 250°C (Bank, 2006), hence decomposition (or softening) of the constituents in a non-metallic timber connection are expected to occur at temperatures well below 610°C. Therefore, temperatures of 610°C are sufficient to achieve failure of the test specimens. Tests of metallic and non-metallic connections were performed under sustained tensile loads of 20% and 40% of the experimentally determined capacity of the connection at ambient temperature. The loads were applied at a constant rate, according to timber test standards (BSi 1991), so that the required load was reached within two minutes and the heating sequence commenced 140 seconds after the initiation of the load at a rate of 15°C/min until a temperature of 610°C was reached or failure of the specimen was observed. The test specimens contained two flitch plate connections, and the load was applied outside the chamber (see Figure 2). Both metallic and non-metallic connections were tested so as to compare their behaviour and failure modes at elevated temperatures.

Table 1: Overview of loaded tests in environmental chamber

Test series	Description	Number of tests loaded at 40% of the ambient capacity	Number of tests loaded at 20% of the ambient capacity	Number of tests without mechanical load (0%)	Average ambient capacity, determined from 4 samples (kN)
FA	Non-metallic connection	3	3	1	9.2
FB	Metallic connection	1	1	1	21.9
FC	Non-metallic connection with minimum edge distance	2	3	1	9.2
FD	Non-metallic connection loaded perpendicular to the grain	2	3	1	3.8

Table 1 gives an overview of the tests that were carried out in the environmental chamber. The specimen dimensions of the different test series, namely FA, FB, FC and FD, are shown in Figure 3**Error! Reference source not found.**. Test series FB has similar specimen dimensions to FA and was designed for a comparative study between non-metallic and metallic connections at elevated temperatures. A reduced end distance of 50mm was adopted for non-metallic dowels, in agreement with the recommendations of Thomson (2010). Test series FC had a minimum edge distance chosen in accordance with Eurocode 5 (BSi, 2004). In series FA the shortest distance from the surface to the shear plane of the dowel was along the dowel, which is not the case in test series FC. The most significant direction of heat transfer was therefore expected to be different for these series of tests. All unloaded tests were performed on specimens instrumented with 12 thermocouples located at various depths from the specimens' exposed surfaces, as shown in Figure 3. Furthermore, Table 1 shows the average ambient capacity, determined from the ambient strength of four control specimens tested for each type of specimen.

2.2 Tests with constant incident heat flux

The influence of differences in thermal properties of LVL, GFRP and DVW on heat transfer was studied using a standard cone calorimeter (BSi, 2002). Specimens containing one (e.g. LVL) or more (e.g. LVL plus dowel) of the relevant materials were subjected to a constant incident heat flux of 50 kW/m^2 (Figure 4). Thermocouples were located at different depths in the specimens to measure the thermal gradients during the tests.

The cone calorimeter is designed to expose small samples to a homogeneous heat flux over its surface and allows study of pseudo one-dimensional heat transfer in the sample under carefully controlled conditions. However, the heat flow in the sample can never be perfectly one-dimensional, as heat losses through the non-exposed sides of the specimen will always occur. A layer of aluminium foil and two layers of 3mm ceramic paper were used as boundary conditions to limit heat losses through the sides of the samples. By limiting heat flow in horizontal directions, almost one-dimensional heat flow can be achieved. The effectiveness of the boundary conditions was evaluated using the test data.

Four test series, namely CA, CB, CC and CD, were performed to study the in-depth temperature evolution of the different connection materials used in this study. The specimen dimensions and thermocouple positions are shown in Figure 5. Test series CA aimed to confirm that the heat was evenly distributed and the heat losses through the sides were insignificant. Test series CB aimed to show the influence of a GFRP dowel on the heat transfer in LVL. As previously discussed, the flitch plate in the gap between two opposing beams can be protected using an intumescent layer (Figure 1). The effectiveness of this layer was studied using series CC. Finally, series CD allowed a comparative study of the heat transfer through LVL and the in-plane heat transfer through DVW sheets. All specimens were tested in triplicate, with the exception of Series CD, which had only one specimen.

2.3 Tests with varying incident heat flux

The Heat-Transfer Rate Inducing System (H-TRIS) is a novel testing system developed at the University *of* Edinburgh (Maluk et al., 2015) in which the position of an array of high intensity propane-fired radiant heat panels is actively controlled (Figure 6) so as to vary the time-history of the incident heat flux imposed on medium scale test specimens. Although similar techniques have been widely used within the fire science community, this novel approach resulted from a change in attitude towards controlling thermal exposure not by temperature, as in standard fire resistance tests in furnaces, but rather by incident heat flux. In contrast with standard furnace tests, which are expensive, time-consuming, and suffer from numerous inherent problems (e.g. low repeatability and homogeneity), H-TRIS tests are inexpensive and highly repeatable.

The set of H-TRIS tests was performed aiming at determining the influence of the non-metallic dowels, flitch plate and intumescent layer on the thermal response of timber connections in fire. The samples consisted of full flitch plate connections. Fifteen thermocouples measured temperatures at different positions at different depths within the connections. Four H-TRIS tests of 60 minutes duration were performed using a *simulated* standard fire exposure. The positions of the thermocouples are shown in Figure 7. Two of the specimens contained an intumescent layer to protect the flitch plate. Additionally, two similar specimens were tested without the intumescent protection. The applied incident heat flux curve (shown in Figure 8) was defined based on the outcomes of a previous study (see Maluk et al., 2015) aimed at replicating the thermal exposure experienced by concrete specimens during standard fire resistance furnace tests controlled to follow the standard time-temperature curve (BSi, 2012).

Also in this test it was important that heat losses or gains from the non-exposed sides were limited. Aluminium foil was tightly wrapped around the sides of the specimen. The specimen was surrounded by 25 mm thick ceramic fibre board (Figure 6). This board was also used to protect the sample holder.

3 Results and analysis

3.1 Loaded tests in the environmental chamber

The time-history of the crosshead displacements of test series FA and FB are shown in Figure 9, in which the black and grey curves represent the non-metallic and metallic connections, respectively. The three different failure modes that occurred are denoted in the legend. Embedment failure occurred in both metallic dowel specimens. The failure mode that generally occurred in the non-metallic dowel specimens was flitch plate failure; this occurred in the locations shown in Figure 12. The failure mode represented by the square point in Figure 9 is deemed as invalid given that the failure in the slender part of the flitch plate was due to lack of protection from the aluminium foil and ceramic paper, rather than in the connection proper. It can be seen that the non-metallic connections had a longer time to failure (54 and 66 minutes on average for 40% and 20% load levels, respectively) than the metallic connections. This is more significant for connections with a 20% load level.

Figure 10 shows the cross-head movement during the test for Series FC. Clear similarities can be seen with the results of Series FA. However, the time to failure was more than 10 minutes less. Specimens in Series FC contained a minimum edge distance of 30mm, which allowed more rapid heat transfer to the dowel than Series FA.

The connections loaded at 20% showed flitch plate failure, similar to Series FA. The connections with 40% load showed embedment failure and shear plug failure. Shear failure of the dowel was also observed in one shear plane.

Results of test Series FD are shown in Figure 11. All specimens showed tensile failure perpendicular to the grain, and the time to failure was less than the parallel-to-grain specimens of Series FA. Specimens of series FA and FD had a similar cross sections and load levels. The main difference was the load grain angle, which must have caused the lower time to failure. The tests conducted in the environmental chamber led to consistent results with a few notable exceptions. For instance, one test at 20% load showed a relatively short time to failure. This specific test displayed excessive deformation during the loading phase (Figure 11). Despite the high predictability of the LVL used in the current study, an imperfection or an initial crack in the timber near the dowel could cause premature failure. However, it can be argued that the mechanical properties of timber perpendicular to the grain are more variable than parallel to the grain (FPL, 2010).

Table 2: Average temperatures after 50 minutes of testing

	Average temperatures (°C)				**TC depth (mm)**	**Material**
	FA0%	**FB0%**	**FC0%**	**FD0%**		
TC 1 & TC 7	356	391	559	354	15	LVL
TC 4 & TC 10	**306**	**377**	**501**	**302**		**GFRP/Steel (dowel)**
TC 2 & TC 8	134	242	413	231	30	LVL
TC 5 & TC 11	**104**	**310**	**354**	**173**		**GFRP/Steel (dowel)**
TC 3 & TC 9	106	328	264	216	45	DVW/Steel (flitch plate)
TC 6 & TC 12	**102**	**343**	**281**	**146**		**GFRP/Steel (dowel)**

Average Temperature range in dowel (°C)	204	67	220	156

Measured temperatures after 50 minutes of heating in tests without mechanical load are shown in Table 2. The names indicate the test series and the load level (FA0%, FB0%, FC0% and FD0%). The averages of thermocouples that were located in the same material and the same depth are shown (e.g. the average temperature measured by TC 2 and TC 8 in test FA0% was 134°C). Temperatures shown in bolt text were located in the dowel. It can be seen that the temperature range in the steel dowel was significantly smaller than the temperature range in the GFRP dowels, showing that the heat was conducted more rapidly along the steel dowel.

As mentioned before the specimens of series FA and FB had similar dimensions. However, the measured temperatures at 30 and 45mm from the exposed surface were significantly lower in the non-metallic connections, which confirms that considerably less heat was transferred into the non-metallic connections. Longitudinal sections of the non-metallic specimen FA0% and metallic specimen FD0% (Figure 13) show important differences in charring behaviour. The non-metallic connection had a clear char layer that was not visibly influenced by the presence of the dowel. This suggests that the heat transfer would be similar in a solid timber block. Heat transfer along the dowel thus appears to be governed by the timber. Figure 13 shows that the timber charred deeper into the connection. The most significant difference can be seen in the surface of the dowel hole. The timber adjacent to the dowel is fully charred in the case of the metallic connection; this is also the location where the timber stresses are highest, which correlates well to the embedment failures that occurred in the mechanically loaded steel dowel specimens.

3.2 Tests with constant incident heat flux

Average test results of the three specimens of Series FA are shown in Figure 14, in which curves with similar line types represent similar distances from the exposed surface. Thermocouples near the exposed surface became loose when the timber burned away and were removed after they lost fixed positions; hence, the discontinuous curves of TC1 and TC7. No significant differences were seen between the central line of thermocouples (TC1 to TC6) and the eccentric line of thermocouples (TC7 to TC12). This indicates that the heat flux to the surface was homogeneous. It also indicates that heat losses or gains from the samples' sides were sufficiently small that one dimensional heat flow was maintained in the area around the thermocouples. Figure 15 shows a section of a typical specimen after an hour of heating. The char depth is constant and is not visibly different on the sides of the specimen. This confirms the homogeneity of the thermal exposure and boundary conditions. Neither temperature measurements deeper than 20mm showed an influence of the cracks, which suggests that the influence of surface cracks on the heat transfer is small or even negligible.

Figure 16 shows average results of test Series CB and shows temperature evolutions very similar to those shown previously in Figure 14. Curves with the same line type represent temperature measurements at the same depth. The black and grey curves show temperatures inside the dowel and LVL, respectively. No obvious temperature differences between the dowel and the LVL or flitch plate were seen. This again indicates that the heat flow was mainly one dimensional. However, it is unlikely that the heat transfer properties of GFRP are identical to those of LVL, resulting in three dimensional heat flow. The similarity of results of Series CA and CB indicate that the timber governed the heat transfer and that the dowel was heated rapidly by the surrounding LVL. Figure 15 shows a section of the specimen after 60 minutes of heating. It can be seen that the charring depth is again constant. This confirms that the heat transfer was not obviously influenced by the dowel, but was governed by the LVL.

From the results of the mechanically loaded tests it appeared that the flitch plate of the connection may fail first in a fire. Series CC aimed to study the effectiveness of an intumescent sealing between two LVL members. From the results shown in Figure 17 it is clear that the temperatures measured in the LVL (grey) were not always similar to the measurements in the intumescent sealing. To show that this is not just caused by variability in test results all data are shown rather than only the averages. Near the surface, the LVL seems to heat up faster than the intumescent layer, while at a depth of 30 mm (TC4 & TC9) the intumescent layer heats up faster than the timber. The temperatures in the two materials were approximately similar at 20 mm depth during the tests. The higher efficiency of the intumescent sealing near the surface can be explained by noting the direction of expansion of the intumescence. Figure 15 shows the char layer after 25 minutes of testing and schematically shows the direction of the heat flow and expansion. Near the surface, the intumescent layer rapidly expands in the direction of the heat source, decreasing the thermal conductivity and increasing the volume. The LVL at this location heats up faster than the intumescent layer, resulting in heat flow by conduction from the LVL to the intumescent layer. This conduction also leads to expansion of the intumescent layer, however it does not lead to a volume increase in the direction of the heat source. Thus, the intumescent layer deeper in the sample is less effective. Solid insulating materials such as ceramic paper could also be considered as protection of the flitch plate in future work; however, an advantage of an intumescent layer is that it fills the void that comes to exist when the timber around the gap shrinks during heating.

Test results of Series CD are given along with the results of Series CA to compare heat transfer through the LVL and DVW in Figure 18. Both materials showed a reduction of heating rate at 100°C due to the energy required to evaporate moisture. At temperatures higher than 100°C the materials show a clear difference in heating rate. This is likely due to the difference in dry density and therefore the difference in heat capacity (for temperatures over 100°C). The DVW showed a lower heating rate in general and a reduction of heating rate at temperatures close to 300°C. According to Frangi (2001) the latter is caused by pyrolysis, which generally takes place in timber at temperatures around 300°C.

3.3 Tests with varying incident heat flux

Figure 19 to 22 show the H-TRIS test results. The grey curves give the temperatures of thermocouples in the lower symmetrical half of the sample and the black curves show the temperatures of the upper half.

Specimens HB and HD had thermocouples located in the flitch plate or the dowel. The results of these tests show significantly less scatter than the results of tests HA and HC in which many thermocouples were located in the LVL. This indicates that DVW has more consistent heat transfer properties than LVL. It also means that results of HB and HD give better insights into the performance of the H-TRIS testing methodology.

Measurements from TC 14 and 15 were taken at the surface and were influenced by direct radiation and convection; these only gave an approximation of the surface temperature. The measurements of TC 14 at the upper half of the connection were higher than the measurements of TC 15 at the lower half during the first 12 minutes of all tests. This is because free convection caused more convective heat losses at the bottom.

TC13 measured the temperature in the centre of the flitch plate in all tests. The differences in measurements from TC 13 in tests HA and HC is clear. The intumescent layer in Test HC protected the flitch plate so that the temperatures only just exceeded temperatures measured at the same depth in the connection. In test series HB and HC the same effect can be seen; from this side the protection is not in line with the heat source and the flitch plate. Nevertheless, the flitch plate was colder in the test with intumescent protection, suggesting heat was conducted from the flitch plate to the intumescent layer.

The measured temperatures from the different tests show no obvious difference. Also no clear difference was found between the temperatures in the LVL members and those in the dowels. Since there was considerably more LVL than GFRP or DVW, this suggests that the heat transfer is governed by the timber.

4. Conclusions

This study has shown the results and analysis of experimental work on the fire performance of non-metallic connections used in heavy timber structures. As shown in this paper, densified veneer wood (DVW) flitch plate and fibre reinforced phenolic dowel connections may be designed to perform appropriately during fire, without cost or aesthetic constraints given by the use of passive fire protection (i.e. fire barriers).

Based on tests performed using a cone calorimeter, H-TRIS, or environmental chamber it can be concluded (regarding non-metallic connections with a fibre reinforced phenolic dowel and a densified veneer wood (DVW) flitch plate in a fire) that:

- the heat transfer along the dowel is governed by the timber;
- no visual effect of the dowel on the char formation in the timber was observed; and
- embedment failure is less likely to occur with non-metallic than with metallic connections.

Tests in an environmental chamber with the specific tested configurations and conditions concluded that:

- failure of the metallic connections occurred faster than failure of the non-metallic connections, under sustained loads of 20% and 40% of the ambient connection capacity;
- the most significant differences were seen at the lower load levels; and
- flitch plate failures limited the fire performance of the non-metallic connections with a 20% load level.

The heat transfer tests conducted with the novel H-TRIS device or a cone calorimeter concluded that:

- the timber (LVL) showed more variation in thermal properties than the DVW;

- the temperature evolution in the in-plane direction of DVW was slower than the temperature evolution measured in the LVL;
- in a connection, the heat transfer in the LVL along the flitch plate is reduced by the flitch plate material;
- an intumescent sealant can be used to successfully protect the flitch plate; and
- this intumescent sealing can enhance the fire performance of the non-metallic connection.

Conclusions regarding metallic connections are drawn from mechanically loaded tests and confirm results of previous studies (e.g. Leicester *et al.,* 1979; Carling, 1989). Namely that unprotected metallic dowels and flitch plates of a timber connection rapidly conduct heat into the connections; this softens the timber adjacent to the metallic members, where the stresses are high, and increases char formation in timber adjacent to the metallic members. Therefore embedment failure is the predominant failure mode for these metallic connections in fires. Finally, an increase of dimensions of the metallic connection will only lead to a limited increase of fire performance. Increasing the dimensions of the non-metallic connection will, on the other hand, result in a much more significant increase of fire performance.

The findings lead to an improved fire performance of dowelled timber connections, which can lead to a significant improvement of the fire performance of whole timber structures. Following research steps will be, structural modelling of the metal free connections in fire and developing simplified design rules for practical use.

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References

Aseeva R, Serkov B, and Sivenkov A. (2014) *Fire Behavior and Fire Protection in Timber Buildings*, Springer, Wien, Austria.

Bank LC (2006) *Composites for Construction: Structural design with FRP materials*, Wiley, Hoboken, NJ, USA.

Bisby L**,** Gales J and Maluk C (2013) A contemporary review of large-scale non-standard structural fire testing. *Fire Science Reviews* **2(1)**: 1-27.

Brandon D, Ansell MP, Harris R, Walker P, Bregulla J (2013) Modelling of non-metallic timber connections at elevated temperatures. *Materials and Joints in Timber Structures*, **9**: 231-241.

BSi (1991) BS EN 26891:1991. Timber structures. Joints made with mechanical fasteners. General principles for the determination of strength and deformation characteristics. *British Standards Institution*, London, UK.

BSi (2002) BS ISO 5660-1. Heat release, smoke production and mass loss rate. Part 1: Heat release rate (cone calorimeter method). *British Standards Institution*, London, UK.

BSi (2004) BS EN 1995-1-1:2004. Eurocode 5: Design of timber structures – Part 1.2: General – Structural fire design. *British Standards Institution*, London, UK.

BSi (2012) BS EN 1363-1:2012: Fire Resistance tests – Part 1: General requirements, *British Standards Institution*, London, UK.

Buchanan AH (2002) *Structural design for fire safety*, Wiley, Chichester, UK.

Buchanan AH, Ostman BAL, Frangi A (2014) *Draft report: Fire resistance of timber structures.* National Institute of Standards and Technology. See http://www.nist.gov/el/fire_research/upload/NIST-Timber-Report-v4-Copy.pdf (accessed 04/02/2015)

Carling O (1989) Fire resistance of joint details in load bearing timber construction – a literature survey. *Building Research Association of New Zealand*, Porirua, New Zealand, BRANZ Study Report SR18.

Drake RD, Aram JWE, Ansell MP (1998) The performance of pultruded GRP connectors in multiple dowelled double shear timber joints, *Journal of the Institute of Wood Science* **14(6)**: 277-283.

FPL (2010) *Wood handbook: wood as an engineering material*, Forest Products Laboratory (FPL) within the U.S. Department of Agriculture, Madison, WI, USA, General Technical Report FPL-GTR-190.

Frangi A (2001) Brandverhalten von Holz-Beton-Verbunddecken (in German). PhD Thesis. *Eidgenössische Technische Hochschule (ETH) Zürich*, Zürich, Switzerland.

Frangi A, Erchinger C, Fontana M (2010) Experimental fire analysis of steel-to-timber connections using dowels and nails. *Fire and Materials* **34(1)**: 1-19.

Gerard R, Barber D, Wolski A (2013). *Fire safety challenges of tall wood buildings*. Arup North America, San Francisco, CA, and Fire Protection Research Foundation, Quincy, MA, USA.

Gottfried JS, Rein G, Bisby LA, Torero JL (2010) Experimental review of the homogeneous temperature assumption in post-flashover compartment fires. *Fire Safety Journal* **45(4)**: 249-261.

Harmathy TZ, Lie TT (1970) Fire Test Standard in the Light of Fire Research. In *Fire Test Performance - ASTM Special Technical Publication 464.* American Society for Testing and Materials, Philedelphia, Pa, USA, pp. 85-97.

Law M (1981) Designing fire safety for steel – recent work. In *Proceedings of the ASCE Spring Convention*. American Society of Civil Engineers, New York, NY, USA, pp. 11–15.

Law A, Gottfried JS, Gillie M, Rein G (2011) Structural engineering and fire dynamics: advances at the interface. *Fire Safety Science* **10**:1563-1576.

Leicester RH, Seath C, Pham L (1979) The fire resistance of metal connectors. In *Proceedings of the Nineteenth Forest Products Research Conference*, Melbourne, Australia.

Leijten AJM, Ruxton S, Prion H, Lam F (2006) Reversed-Cyclic Behavior of a Novel Heavy Timber Tube Connection. *Journal of Structural Engineering* **132(8)**: 1314-1319.

Maluk C (2014) Development and application of a novel test method for studying the fire behaviour of CFRP prestressed concrete structural elements. PhD Thesis, *The University of Edinburgh*.

Maluk C, Bisby L, Krajcovic M, Torero JL (2015) The Heat-Transfer Rate Inducing System (H-TRIS) Test Method. *Fire Safety Journal*. (sent to editor)

Moss PJ, Buchanan AH, Fragiacomo M, Lau PH, Chuo TC (2009) Fire performance of bolted connections in laminated veneer lumber. *Fire and Materials* **33(5)**: 223-243.

Naughton A, Fan M, Bregulla J (2014) Fire resistance characterisation of hemp fibre reinforced polyester composites for use in the construction industry. *Composites Part B*: **60**: 546-554.

Östman BAL and Tsantaridis LD (1994) Correlation between cone calorimeter data and time to flashover in the room fire test. *Fire Materials* **18(4)**: 205–209.

Östman BAL et al, 2010. *Fire Safety in Timber Buildings-Technical Guideline for Europe*.
Technical research institute of Sweden, Stockholm, Sweden, SP Report 2010:19.

Palma P, Frangi A, Hugi E, Cachim P and Cruz H (2014) Fire resistance tests on beam-to-column shear connections. In P*roceedings of the 8th International Conference on Structures in Fire*, Tongji University Press, Shanghai, China, 545-556.

Pedersen MU (2002) *Dowel type timber connections – Strength modelling*. Danmarks Tekniske Universitet, Lyngby, Denmark, Report BYG DTU R-039 2002.

Peng L, Hadjisophocleous G, Mehaffey J, Mohammad M (2010) Fire resistance performance of unprotected wood-wood-wood and wood-steel-wood connection: A literature review and new data correlations. *Fire Safety Journal* **45(6-8)**: 392-399.

Sachs EO (1903) Suggested standards of fire resistance. In *Proceedings of the International Fire Prevention Congress*, London, England, 249-252.

Thomson A, Harris R, Ansell MP, Walker, P (2010) Experimental performance of non-metallic mechanically fastened timber connections. *The Structural Engineer* **88(17)**: 25-32.

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