# On the design of timber bolted connections subjected to fire

**Peter MOSS**
**Associate Professor of Civil Engineering**
**University of Canterbury**
**Christchurch, New Zealand**

**Massimo FRAGIACOMO**
**Associate Professor of Structural Design**
**University of Sassari**
**Alghero, Italy**

**Carla AUSTRUY**
**Master student**
**Ecole normale superieure de Cachan**
**Cachan, France**

**Andrew BUCHANAN**
**Professor of Timber Design**
**University of Canterbury**
**Christchurch, New Zealand**

## Summary

Current research at the University of Canterbury is investigating the application of Johansen's yield equations to the prediction of the failure strength of bolted connections in fire conditions. A series of single bolted connections using steel side plates have been heated at constant temperature for several hours, then loaded to failure. The failure loads have been used to determine the embedment strength of the joints at various temperatures over a range of temperatures from ambient to 300°C. These temperature-dependent embedment strengths have also been used in the Johansen's equations for wood-steel-wood and wood-wood-wood connections and compared with the results for single bolted connections tested over a range of constant temperatures. Comparisons have also been made with the results of several similar connections tested in fire conditions and show considerable promise for predicting failure of such joints.

## 1. Introduction

Fire is unpredictable and dangerous, especially in residential buildings. The effects of fire on timber structural members are very complex because of the large number of variables involved. Once ignition has occurred, then a layer of char forms as the wood burns. A structural wood member will lose load capacity as the wood is converted to charcoal which has no strength. The thickening char layer protects the remaining wood, resulting in a predictable rate of charring below the surface. The rate of development of this charred layer determines how long the member can continue to carry load before the strength of the remaining unburned wood material is exceeded. A thin layer of heat-affected wood below the char layer will have reduced strength and stiffness.

In recent years, a number of research papers have been published on the influence of temperature on the mechanical properties of wood [e.g. 1, 2, 3, 4]. Research has also been carried out into the performance of joints in timber members when subjected to fire temperatures [e.g. 5, 6, 7, 8, 9]. Particular research into the embedment strength of wood at elevated temperatures has also been carried out [10, 11].

Moraes et al [10] carried out embedment tests at temperatures ranging from 20ºC to 240ºC. The 8 mm diameter dowel specimens were heated for 2 hours before testing to a maximum displacement of 5 mm. They found that the embedment strength at 80ºC was 30% lower than at 20ºC but then rose to a peak at 140ºC where it was 15% lower than at 20ºC and then decreased to 40-50% at 240ºC. The tested specimens showed that the moisture content decreases linearly with increase in the test temperature. The specimens had a moisture content of about 5% at 80ºC and were found to be almost oven dry at 140ºC.

For some time now, the European timber code [12] has used formulae based on Johansen's yield equations [13] to predict the strength of timber connections under ambient conditions. Eurocode 5 [14] gives some guidance for predicting the strength of connections during fire conditions. Carling [15] defined failure as occurring when the rate of displacement exceeds 10 mm/min, or the total displacement exceeds 15 mm. He also proposed a formula for calculating the time to failure for bolted connections, based on his experimental testing.

This paper describes an experimental investigation to determine the axial tensile strength of a bolted connection that utilised steel or timber splice plates to connect timber members made from LVL (laminated veneer lumber). Single-bolted connections were tested under constant temperature conditions to determine the embedment strength of the LVL over a range of temperatures. The variation of the embedment strength was then used in Johansen's equations (as presented in EC5 [14]). The purpose of the research was to investigate the relationship between the embedment strength of LVL timber and the time to failure of the connections when exposed to fire.

## 2. Background to the Testing

The design for the connection tested previously by Lau [16], Chuo [17] and Moss et al. [18] was based on a tensile member in the bottom chord of a floor or roof truss. The timber (LVL) members being joined were 150 × 63 mm. The design properties of the LVL are shown in Table 1. The steel side plates were 6 mm thick. The bolts were 12 mm diameter and were made of Grade 4.6 steel.

*Table 1 Limit state properties for design with NelsonPine LVL [19].*

| | | |
|---|---|---|
| **Elastic Moduli** | | |
| Modulus of elasticity | E | 10.7 GPa |
| Modulus of rigidity | G | 660 MPa |
| **Characteristic Strength** | | |
| Bending | $f'_b$ | 42 MPa |
| Tension parallel to grain | $f'_t$ | 22 MPa |
| Compression parallel to grain | $f'_c$ | 35 MPa |
| Shear in beams | $f'_s$ | 6.0 MPa |
| Compression perpendicular to grain | $f'_p$ | 12 MPa |

The design load on the joint was taken to be 40% of the ultimate tensile strength of the LVL in cold conditions (i.e. a load of 40% of 221 kN = 88 kN) by assuming that other design conditions will be more critical than the tensile strength of the member. With a calculated load factor of 0.33 for fire conditions, this gave an expected fire load of 29 kN. Six bolts were used for the Wood-Wood-Wood (W-W-W) joint, four bolts for the Steel-Wood-Steel (S-W-S) joint, and five bolts for the Wood-Steel-Wood (W-S-W) joint.

The same size timber and steel members were used to fabricate single-bolt joints with 12 mm diameter bolts. The bolts were placed on the member centreline with an end distance of 100 mm, i.e. eight bolt diameters, as shown in Figure 1 for the three different connections.

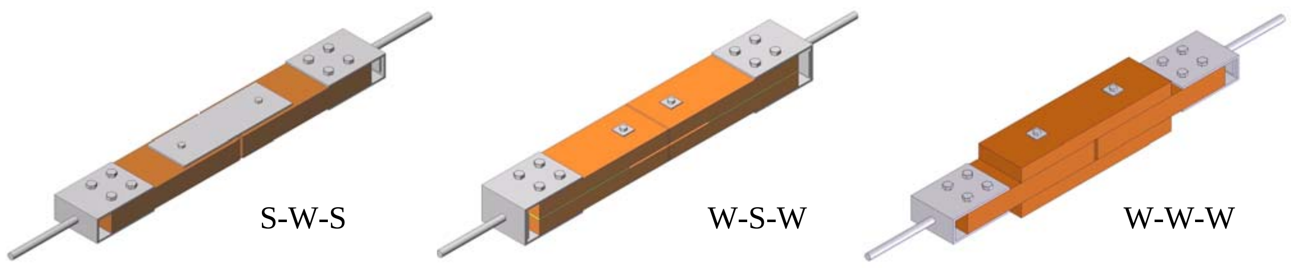


*Fig. 1 The three types of connection tested. Multi-bolted specimens were also used in fire tests.*

## 3. Heated testing

*Fig. 2 The test frame and furnace used for the heated tests and fire testing.*

In order to develop a simple method of predicting the load capacity and deformation of connections in timber structures when exposed to known heat flux, a series of tests were carried out at known temperatures in a similar manner to that outlined in previous research [10, 11]. For this testing, a series of single-bolt joints were heated in the furnace for two hours at a constant temperature with no applied load under temperatures ranging from ambient to 280°C. The test specimens were then quickly loaded to failure in accordance with the loading protocol suggested by ISO 10984-2 [20]. The furnace used for both the heated tests and the fire tests is shown in Figure 2.

### 3.1 Embedment Strength

Since the S-W-S connections were similar to standard embedment test specimens, the results from these tests were used to evaluate a form of embedding strength for the LVL at elevated temperatures. The main differences between the single-bolt joints tested and the testing apparatus as required by ISO 10984-2 [20] are outlined in Table 2.

*Table 2 Comparison of single-bolt connection and ISO standard embedment test*

| | Single-bolted SWS connection | ISO Standard Embedment Test [20] |
|---|---|---|
| 1. | Steel members tightly bolted to timber member (Fig. 1). | No contact between steel members and test specimen. |
| 2. | Two fasteners were used in each test (i.e. one at each member end). | Only one fastener used in test. |

The embedment strength was calculated by dividing the critical load by the bearing area (product of bolt diameter and thickness of the member), assuming a mode j/l failure as shown in Figure 6. The "embedment strength" in the ISO standard is based on either the maximum load or the load at 5 mm displacement, depending on which occurs first. As our bolted connection contained two bolts (one at each member end as shown in Figure 1) and the maximum load occurred at a large displacement, the critical load was taken as either the load at 10 mm displacement, or the maximum load. For connections where there was bending of the bolt (mode k in Figure 6), the embedment strength was calculated from the relevant Johnasen's yield formula from EC5, including the calculated bending strength of the bolt at elevated temperature.

The results for embedment strength vs temperature are shown in Figure 3 where it can be seen that the embedment strength decreases as the temperature increases, reaching a minimum at about 110ºC and then increasing as the temperature increases further to 180ºC, followed by a decrease with further temperature increase. The data points shown by triangles in Figure 3 are the embedment strengths determined later using 45 mm thick LVL and 12 mm thick splice plates, where the thinner thickness of LVL fully complies with the thickness to bolt diameter ratio recommended by the ISO standard [20] for embedment strength tests. The approximation 1 of Figure 3 shows the embedment strength based on the load at 10 mm displacement while approximation 2 is the same, except that the embedment strength is now taken as independent of temperature for all temperatures below 20 ºC and above 260 ºC (or minimum strength of 10MPa).

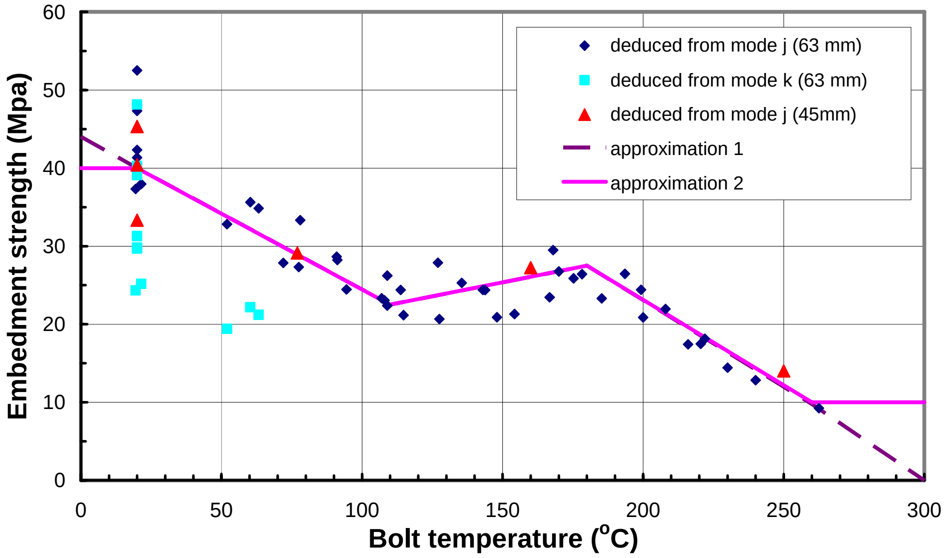


*Fig. 3 LVL embedment strength based on load at 10 mm displacement, and with cut-off below 20°C and above 260°C.*

### 3.2 Prediction of fire resistance

The temperatures of the air, the steel plate-wood interfaces, and at several points on the bolts (all measured using thermocouples) are shown in Figure 4 for the S-W-S connection during a typical fire test. It can be seen that the temperatures of the steel side plates and the bolts are effectively the same, with no temperature gradient along the bolt. Figure 5 for the W-W-W connection, on the other hand, shows that it takes longer for the bolt at the centre of the centre member to heat up than it does for the bolt head which is exposed to the fire, with a big temperature gradient along the bolt.

For the S-W-S connections, the experimental failure mode for the bolts at ambient temperatures was mode k whereas for temperatures above 50ºC the failure mode was mode j/l (see Figure 6 for sketches of these failure modes). The comparison between the experimental results and the predicted failure loads using Johansen's equations, and the approximation for the embedment strength shown in Figure 3, are plotted in Figure 6 for modes j/l, k and m, together with the maximum experimental failure loads. It can be seen that, in general, almost all the maximum experimental loads fall on or above the predicted values for failure mode j/l except at 20ºC where the experimental failure loads are scattered about the predicted value for mode k.

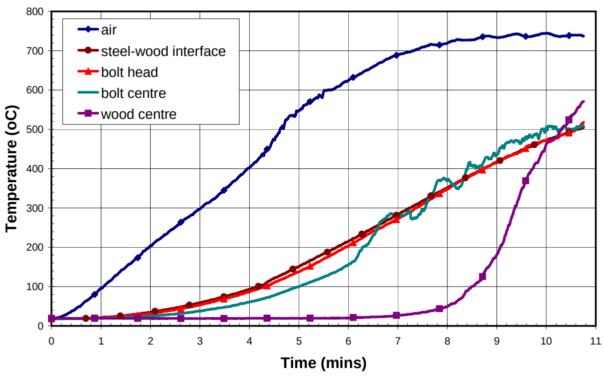


*Fig. 4 Temperatures measured within the S-W-S connection during the fire test.*

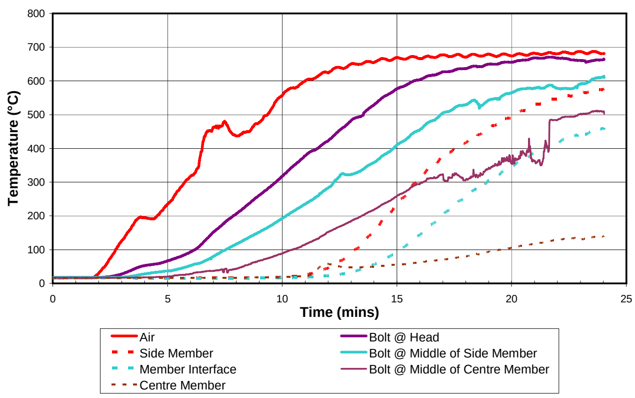


*Fig. 5 Temperatures measured within the W-W-W connection during the fire test.*

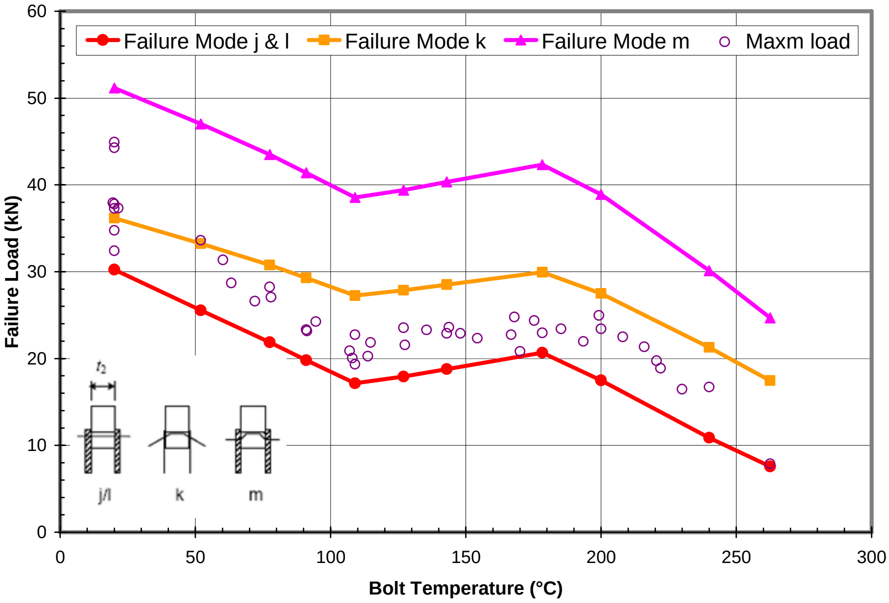


*Fig. 6 Predicted failure loads and maximum experimental loads for single-bolt S-W-S connections tested at constant temperature.*

## 4. Failure prediction for fire tested connections

Using the experimental embedment strength calculated from the single bolt S-W-S connection tests, the predicted failure loads in fire for the three connections tested with single bolts are shown in Figures 7-10. The contact thickness between the bolt and the timber members was taken as the original thickness less the thickness of the charred surface as indicated in Equation 1.

$$t_{contact} = t - (n \times D \times \theta) \quad (1)$$

where $t$ = Original timber thickness (mm)
$n$ = Number of charring surfaces (-) (for SWS, n = 2, otherwise n = 1)
$D$ = Experimental charring rate (mm/min)
$\theta$ = Charring duration (min)

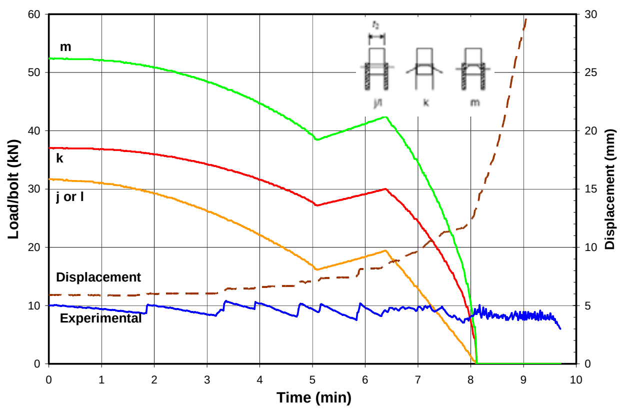


*Fig. 7 Predicted failure loads for a S-W-S connection based on Fig. 3 approximation 1.*

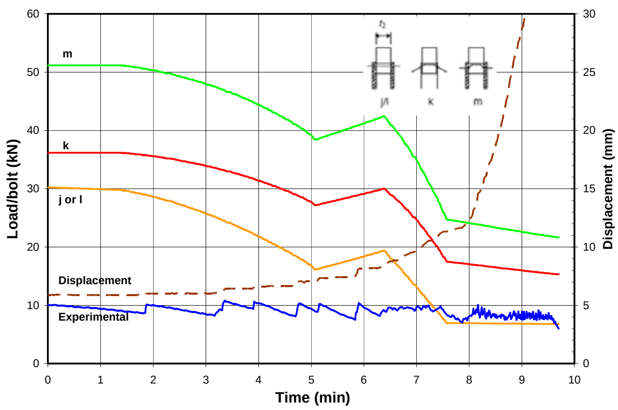


*Fig. 8 Predicted failure loads for a S-W-S connection based on Fig. 3 approximation 2.*

In order to derive the curves for the various failure modes shown in Figures 7-10 it is necessary to know the temperature in the bolt over time, T(t), then determine the embedment strength, $f_h(T(t))$ using the approximation depicted in Figure 3 and the yielding moment for the bolt, $M_y(T(t))$. These are then substituted into the Johansen's equations. The reduction of strength during fire exposure is due to the change in embedment strength and the reduction of the contact thickness during the fire.

These calculations were made using the average measured bolt temperatures, assuming uniform temperature along each bolt. Numerical studies are presently under way to predict T=T(t) during a fire, depending on the geometry of the joint, which should enable a future relationship to be established between the fire temperature and the temperature in the bolts.

The prediction of the failure mode and the failure load per bolt for the S-W-S connection using the tri-linear embedment strength curve of approximation 1 of Figure 3 (Figure 7), together with the experimental charring rate and steel strength reduction factor for temperature, were reasonably accurate. The tests were stopped when the total displacement reached 30-40 mm and the rate of displacement was increasing rapidly. However, the estimation of the failure time was too early compared to the experimental failure time; this is because after the LVL has reached its zero embedment strength, the load carrying capacity of the connection is zero, though experimentally it was still able to carry some load. On the other hand, if approximation 2 of Figure 3 is used to determine the failure time (Figure 8), the prediction seems more accurate, allowing for some cooling of the bolt as it cuts its way into slightly cooler timber. Nevertheless, once the LVL reaches its constant embedment strength in Figs 8 to 10, the load carrying capacity of the connection reduces only slightly as the timber chars and therefore the predicted failure time is very sensitive to the load level.

The predicted failure loads for the W-S-W connection using the approximation 2 of Figure 3 are shown in Figure 9. For this particular connection the predicted failure mode is always mode f. While the prediction looks reasonably accurate, it more clearly indicates a range of time over which failure could take place. For the W-W-W connection, Figure 10 shows the predicted failure loads using the approximation 2 of Figure 3 and how they vary throughout the duration of the fire with mode g being the predicted failure mode. Again, the predicted time to failure looks reasonably accurate, but with a very flat curve after constant embedment strength is reached.

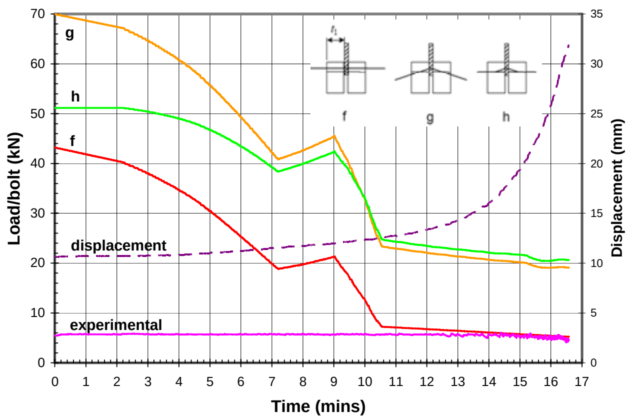


*Fig. 9 Predicted failure loads for W-S-W connection.*

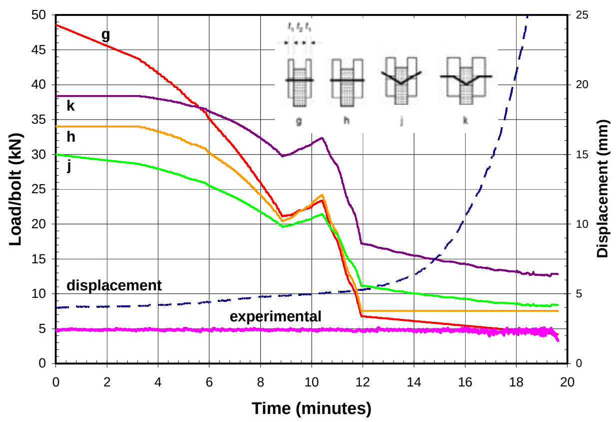


*Fig. 10 Predicted failure loads for W-W-W connection.*

## 5. Discussion

The decrease of embedment strength from 50ºC to about 110ºC is possibly due to softening of the lignin in the cell walls, while the increase in the range between 110ºC and 180ºC is caused by the timber drying and releasing the bound water from the cells, together with possible rehardening of lignin over this temperature range. The embedment strength results described herein are similar to the results reported by Moraes et al [10], and similar to those reported by Young and Clancy [1] and Jong and Clancy [3] for compression parallel to the grain strength of timber.

Since timber chars at around 300ºC and the char layer has negligible strength, it would seem reasonable for the embedment strength values shown in Figure 3 to reduce to zero at about 300 ºC. However, in a connection that is transferring load, the char layer is displaced as it forms and the bolt continues to heat the wood in contact with it. The result is that the bolt cuts an elongated hole in the wood member; this causes movement in the joint but does not necessarily lead to failure and the joint continues to carry load, as there is some cooling of the bolt as it cuts its way into slightly cooler timber. For this reason, it is suggested that the approximation 2 of Figure 3 should be used instead of that of approximation 1.

If we take failure as occurring when the rate of displacement exceeds 10 mm/min, or the total displacement exceeds 15 mm [15], then Figure 8 for the S-W-S connection gives a good prediction of failure since the rate of deflection increases markedly at about 8 minutes and the total displacement exceeds 15 mm shortly after. However, for the W-S-W (Figure 9) and the W-W-W (Figure 10) connections, there is not the same close agreement between the prediction and the definition of failure based on the displacement and its rate of increase.

## 6. Conclusions

The embedment strength of radiata pine LVL can be described by a tri-linear relationship that drops linearly from 40 MPa at 20°C to 25 MPa at 110°C, rises to 27.5 MPa at 180°C, then falls to 10 MPa at 260°C.

This tri-linear embedment strength was used in conjunction with Johansen's yield equations to predict the failure load and the results showed reasonable agreement with the experimental values.

It is difficult to predict the time to failure accurately because the definition of failure is not clearly established, and because there is uncertainly about the actual bolt temperatures and the embedment strength when the bolt temperature exceeds 250°C. The assumption of a lower bound cut-off of embedment strength at 10MPa allowed more accurate predictions of failure time than with the embedment strength dropping to zero.

Future analytical work is needed to provide a more accurate thermal analysis, firstly in the unloaded condition and more importantly in the loaded condition when the hot bolt is cutting through the wood. This then must be extended to multiple bolts and to other dowel-type fasteners such as nails and screws.

## 7. Acknowledgements

Thanks to Nelson Pine for the supply of all the LVL which was tested. Thanks also to David Carshalton for conducting many embedment tests during his summer work experience at the University of Canterbury, and to Bob Wilsea-Smith and Grant Dunlop for laboratory support.

## 8. References

[1] Young S.A., and Clancy P.,. "Compression mechanical properties of wood at temperatures simulating fire conditions", *Fire and Materials,* Vol. 25, 2001, pp. 83-93.

[2] Reszka P., and Torero J. L., "In depth temperature measurements of timber in fires", *Proc. 4th International Workshop on Structures in Fire,* Aveiro, Portugal, 2006.

[3] Jong F., and Clancy P., "Compression properties of wood as functions of moisture, stress, and temperature", *Proc. 2nd International Workshop on Structures in Fire,* Christchurch, New Zealand, 2002, pp. 223-242.

[4] Janssens M., "Modelling of the thermal degradation of structural wood members exposed to fire", *Proc. 2nd International Workshop on Structures in Fire*, Christchurch, New Zealand, 2002, pp. 211-222.

[5] Frangi A., and Mischler A., "Fire tests on timber connections with dowel type fasteners", *Proc. International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures, Meeting 37,* Edinburgh, United Kingdom, 2004.

[6] Erchinger C., Frangi A., and Mischler A., "Fire behaviour of multiple shear steel-to-timber connections with dowels", *Proc. International Council for Research and Innovation in*

*Building and Construction – Working Commission W18 – Timber Structure, Meeting 38*, Karlsruhe, Germany, 2005.

[7] Erchinger C., Frangi A., and Mischler A., “Thermal investigations on multiple shear steel-to-timber connections”, *Proc. World Conference on Timber Engineering*, Portland, Oregon, USA, 2006.

[8] Laplanche K., Dhima D., and Racher P., “Thermo-mechanical modelling of the timber connection under fire using 3D finite element model”, *Proc. World Conference on Timber Engineering*, Portland, Oregon, USA, 2006.

[9] Schabl S., and Turk G., “Coupled heat and moisture transfer in timber beams exposed to fire”, *Proc. World Conference on Timber Engineering*, Portland, Oregon, USA, 2006.

[10] Moraes P.D., Rogaume Y., Bocquet J.F., and Triboulot P., “Influence of temperature on the embedding strength”, *Holz als Roh- und Werkstoff*, Vol. 63, 2005, pp. 297-302.

[11] Chapuis S., Moraes P.D., Rogaume Y., and Torero J.L., “Evaluation of in-depth temperature distributions and embedding resistance of timber in a fire”, *private communication*, 2005...

[12] Eurocode 5 – Part 1-1: *Design of Timber Structures. EN 1995-1-1:2004: General – Common Rules and Rules for Buildings*, European Committee for Standardization, Brussels, Belgium, 2004.

[13] Johansen K.W., “Theory of timber connections”, *Int. Assn of Bridge & Struct. Eng.*, Publ. No. 9, 1949, pp. 249-262, Bern, Switzerland.

[14] Eurocode 5 – Part 1-2: *Design of Timber Structures. EN 1995-1-2:2004: General – Structural Fire Design*, European Committee for Standardization, Brussels, Belgium, 2004.

[15] Carling O., 1991, “Fire behaviour of metal connectors on wood structures”, *Proc. Int. Conf. on Timber Engineering*, London, Vol. 4, 1991, pp. 106-113.

[16] Lau P.H., “Fire resistance of connections in laminated veneer lumber”, Fire Engineering Research Report 06/3, 2006, Dept. of Civil Engineering, University of Canterbury, New Zealand, http://www.civil.canterbury.ac.nz/fire/fe_resrch_reps.shtml.

[17] Chuo T.C.B., “Fire performance of connections in LVL structures”, Fire Engineering Research Report 07/4, 2007, Dept. of Civil Engineering, University of Canterbury, New Zealand, http://www.civil.canterbury.ac.nz/fire/fe_resrch_reps.shtml.

[18] Moss P.J., Buchanan A.H., Fragiacomo M., Lau P.H., and Chuo, T. “Fire performance of bolted connections in laminated veneer lumber”, submitted for publication on *Fire and Materials*, 2007.

[19] NelsonPine NZ LVL10, *Design guides and span tables*, Nelson Pine Industries Ltd, Richmond, Nelson, New Zealand, 2003.

[20] ISO 10984-2, *Timber structures – Dowel-type fasteners – Part 2: Determination of embedding strength and foundation values*, International Standards Organization, Geneva, 1999.