FIRE PERFORMANCE OF CONNECTIONS IN LAMINATED VENEER LUMBER (LVL)

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Summary

This paper describes an investigation into the fire performance of tensile connections in laminated veneer lumber (LVL) made from radiata pine. The capacity of the connections depends on the shear between the wood members which in turn depends on the embedding strength of the wood and on the yield moment of the connectors. The purpose of the research was to investigate the relationship between the failure load of LVL timber and the time to failure of the connections when exposed to fire. To determine connection performance, an experimental investigation was carried out on the axial tensile strength of three types of connection that utilised either wood or steel splice plates. The fasteners tested included bolts, dowels, nails, screws and other connectors, but only bolts are reported here. Some specimens were tested at ambient temperature while similar specimens were tested in fire conditions with a constant applied load.

Introduction

Fire is unpredictable and dangerous, especially in residential buildings. The effects of fire on structural members are very complex because of the large number of variables involved. Once ignition has occurred, 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.

An experimental investigation was carried out on the axial tensile strength of three types of connection that utilised either wood or steel splice plates to connect the LVL members. The specimen arrangements tested were wood-wood-wood (W-W-W), steel-wood-steel (S-W-S), and wood-steel-wood (W-S-W). Some specimens were tested at ambient temperature to determine the ultimate strength of the different types of connection, while similar specimens were tested in fire conditions under constant applied load. The purpose of the research was to investigate the relationship between the failure load of LVL timber and the time to failure of the connections when exposed to fire. The fasteners included bolts, dowels, nails, screws and proprietary connectors. This paper reports only bolted joints, with the tests on others covered elsewhere [1, 2].

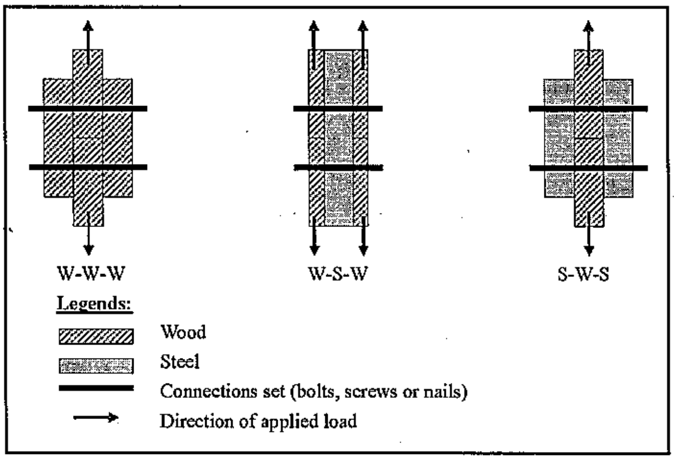

Figure 1 Joint arrangements as tested

Tests carried out

Testing was carried out on three arrangements as shown in Figure 1.

The design was based on a tensile member in the bottom chord of a floor or roof truss. The timber members being joined were 150 x 63 mm. The wood side plates were 150 x 45 mm Steel plates (side or central) were 6 mm thick. The bolts were 12 mm diameter.

The design load on the joint was taken to be 40% of the ultimate strength in cold conditions (i.e. 88kN). With a calculated load factor of 0.33 for fire conditions, this gave an expected fire load of 29kN. Six bolts were used for the W-W-W joint, four bolts for the S-W-S joint, and five bolts for the W-S-W joint. The different connections were fabricated as shown in Figures 2 to 4.

1. Page 5 - It should have been noted that this paper was first presented at the 9th World Conference on Timber Engineering held in Portland, Oregon, USA in August 2006.
2. Page 5 – The name of the employer of one of the co-authors, Mr Lau, is Sinclair Knight Merz NOT Mertz.

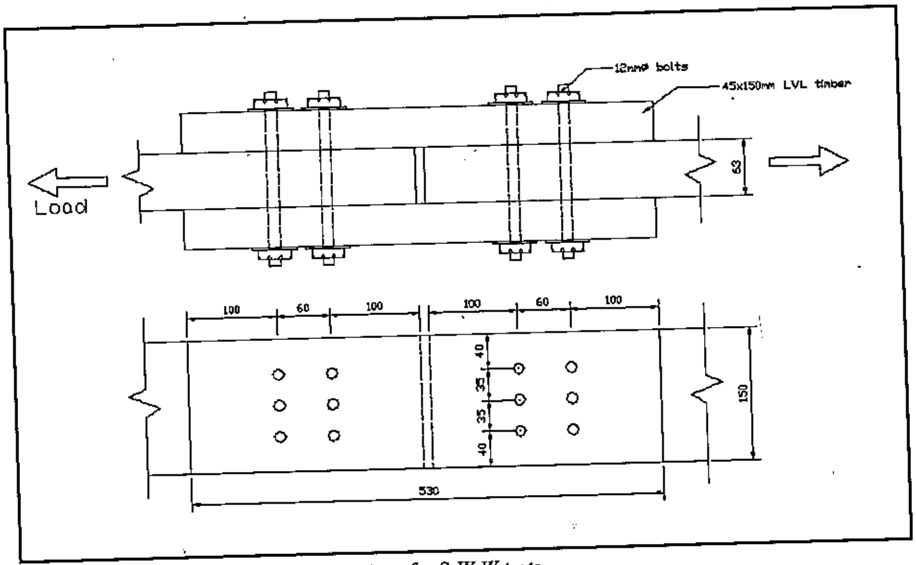

Figure 2 Arrangement of bolted connections for S-W-W tests

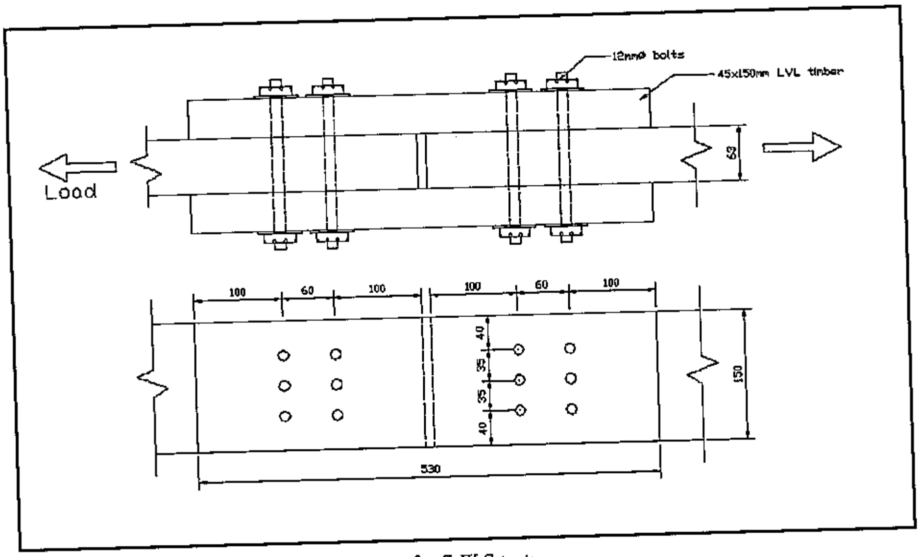

Figure 3 Arrangement of bolted connections for S-W-S tests

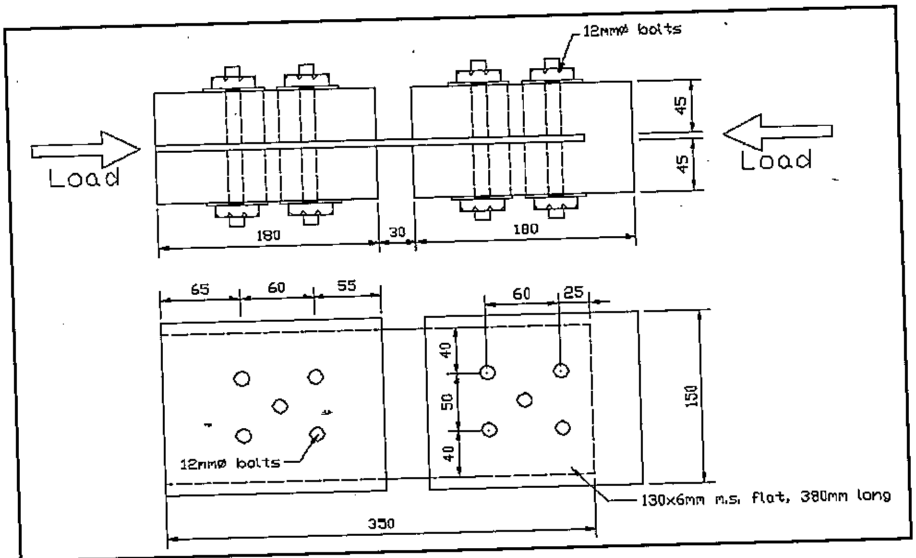

Figure 4 Arrangement of bolted connections for W-S-W bolted joints

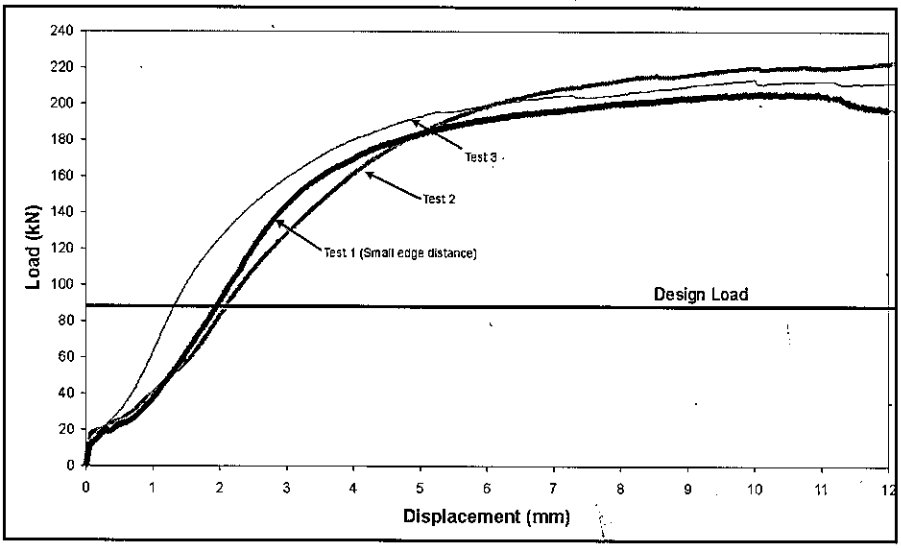

Figure 5 Strength of W-S-W bolted joints

Cold (ambient) testing

All the joints were tested at ambient temperatures to ascertain the likely ultimate strengths relative to the design load. This testing was carried out in compression, rather than tension. The deflection was measured as the load was applied, with two potentiometers at each side. Typical results are illustrated in Figure 5. All the bolted connections reached an ultimate load that was much greater than the code-specified design load.

Furnace testing

A custom-built testing frame with a furnace allowed each specimen to be held under constant load while heat was applied to the surface of the test specimen (Figure 6). Each test specimen was positioned and the air supply was regulated so that the heated specimen was subjected to approximately uniform charring on all sides

Each specimen took between 2 and 5 minutes to begin charring, as evidenced by smoke coming from the furnace. The surfaces of the test specimens were not visible from outside the furnace.

This led to a period where the test specimens were charring and building up pyrolyzates within the furnace, but prior to flaming [3]. After a few more minutes, the gases reached their unpiloted ignition temperature and ignited.

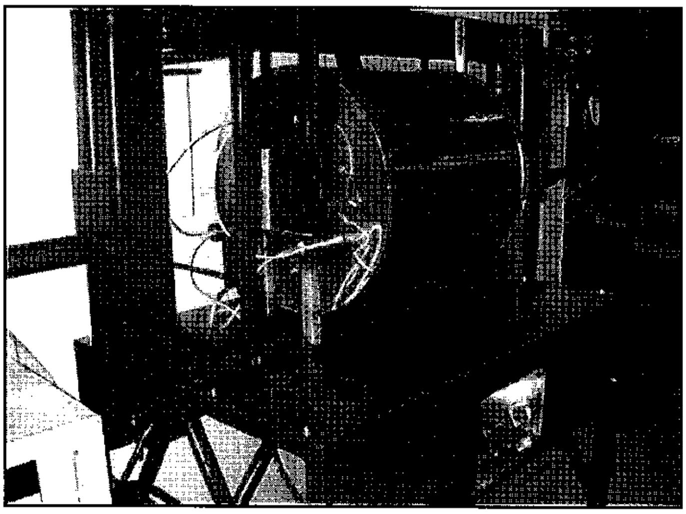

Figure 6 The test frame used for furnace testing

There were flames on all surfaces of the test specimens from the time of ignition until the conclusion of the test. When the test specimens failed, the furnace was switched off and the specimens were quickly removed from the furnace. The flames were then extinguished and the specimens cooled with water to prevent further charring.

Table 1 - Time to failure for furnace testing

Connections	Sample	Time to charring (min)	Time to ignition (min)	Time to failure (min)
W-W-W	Bolts 1	3.0	4.9	23.2
	Bolts 2	2.8	4.0	21.7
S-W-S	Bolts 1	3.0	4.5	11.5
	Bolts 2	3.5	4.5	11.3
W-S-W	Bolts 1	3.0	4.3	19.0
	Bolts 2	3.2	4.3	19.5

Time to Failure

The experiments started when the constant load of 29kN was first applied. The failure time was the time at which this load was not able to be sustained. The results are shown in Table 1. Figures 7 to 9 show typical connections after testing.

Not only has the LVL suffered considerable charring, but the bolts have cut elongated slots in the LVL as they heated up during the fire. Figure 10 shows that the heating from the electric coils in the furnace was not able to heat the furnace as rapidly as the standard ISO 834 fire curve.

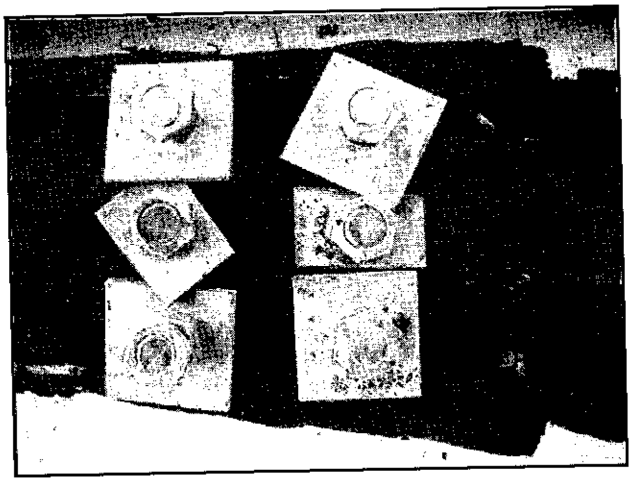

Figure 7 Condition after furnace tests of W-W-W- bolted connection

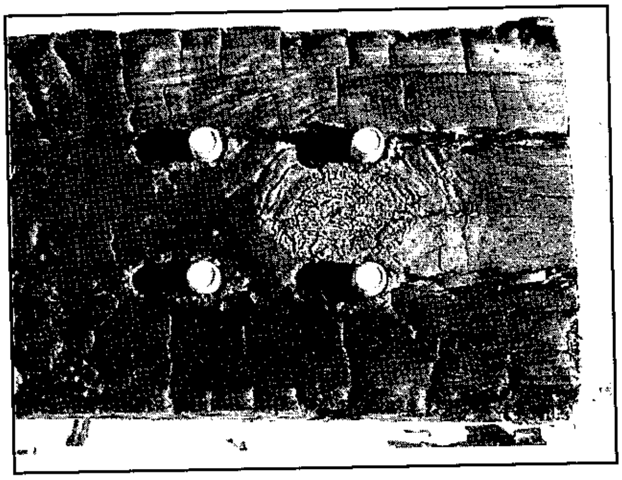

Figure 8 Failure mode of S-W-S bolted connections

Figure 9 Failure mode of W-S-W bolted connections

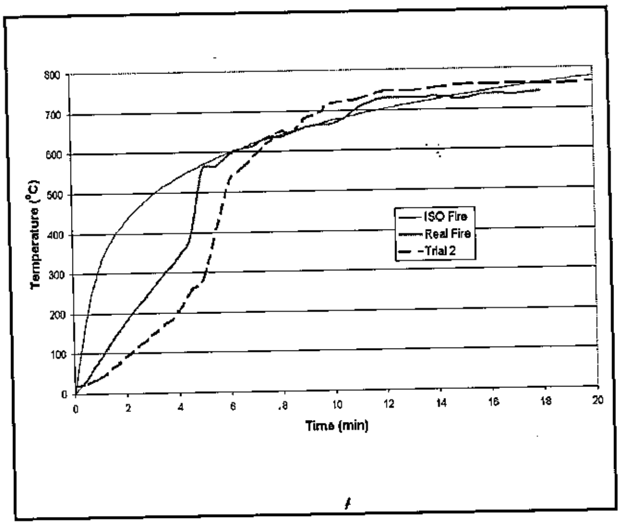

Figure 10 Comparison between ISO 834 fire curve and furnace temperatures for two typical tests

Prediction of Fire Resistance

Because the furnace did not follow the standard ISO 834 fire, the time of failure in the tests was not the same as the fire resistance of the connections. To convert from the time of failure to an estimated fire resistance, the fire severity on the surface of the timber piece and the rate of char were analysed.

During a fire, a layer of char forms over the surface of unburnt timber which then shrinks and burns away after a period of time. The fire resistance of the cross section is based on the residual cross section after charring. The base of the char layer is at approximately 300°C, with a heated layer below the char front. The part of this layer above 200°C is known as the pyrolysis zone which is undergoing thermal decomposition into gaseous pyrolysis products, accompanied by loss of weight, loss of strength and discolouration [4].

To assess the charring rate of the timber, the char layer was removed after testing and the remaining timber section was measured. The char rates in columns 4 and 5 of Table 2 are averages over the duration of the test, which is the observed depth of char divided by the total duration of exposure, including the period at the beginning of the test before the onset of char. This was consistent with the testing procedure of Lane et al.[5] who provided the standard furnace charring data used for comparison [3].

It can be seen that the charring rates for the test specimens in the furnace range from 0.53 mm/min up to 0.70 mm/min, with a mean value of 0.65 mm/min. This was slightly lower than the average charring rate observed in the ISO 834 furnace by Lane et al.[5] of 0.72 mm/min. Harris [3] developed a formula to convert the failure time in the furnace to failure time in a standard fire (fire resistance):

$$t_{ISO} = \frac{c_{cust}}{c_{ISO}} t_{cust}$$

tISO	=	Fire resistance time in ISO furnace (minutes)
tcust	=	Time exposed in the custom furnace
cISO	=	Char rate recorded in the ISO furnace (0.72 mm/min)
ccust	=	Char rate recorded in the custom furnace (mm/min)

The actual durations in the furnace were converted to expected durations in the ISO fire, or the fire resistance.

The results are shown in columns 6 and 7 of Table 3.

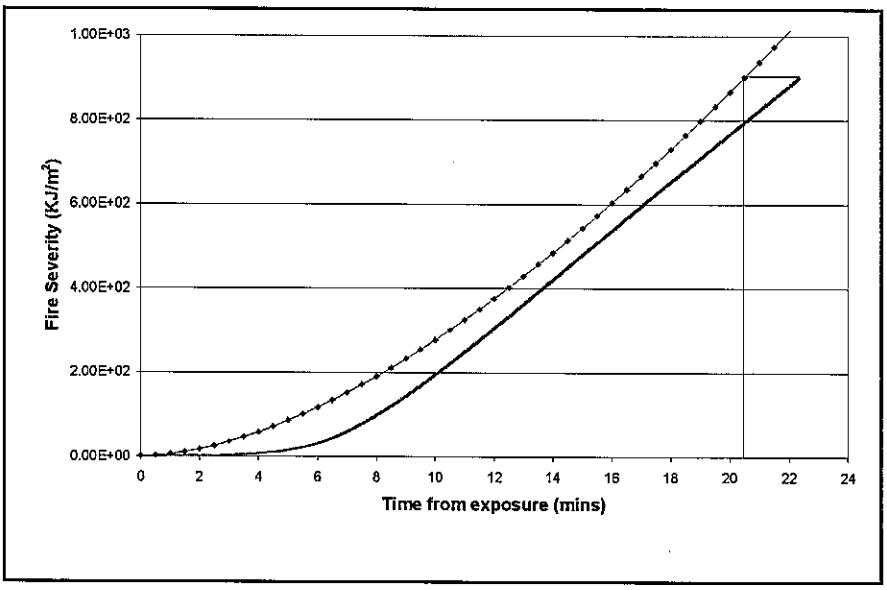

Figure 11 Correlation between time of exposure and fire severity for W-W-W bolted connection.

The fire resistance of the connections was also determined using the "radiant exposure area correlation" concept suggested by Nyman [6]. In this method, the measure of fire severity is the cumulative radiant heat exposure at any time.

The radiant heat exposure in the test fire can be compared with that in the ISO 834 fire to give an equivalent fire resistance.

For example, in Figure 11 the fire severity curve for the connection is similar in shape to the fire severity curve of the ISO 834 fire curve, and the test connection failed at 22.5 minutes which is equivalent to 20.5 minutes exposure to the standard fire.

Page 9 – The sentence just above Figure 11, should read "The results are shown in columns 6 and 7 of Table 2." Tables 2 was missing – it is included below.

Table 2 Char rates and calculated fire resistance using the charring rate method

Column 1 Connections	2 Sample	3 Time to failure (min)	4 Depth of char (mm)	5 Average char rate (mm/min)	6 Calculated fire resistance (mins)	7 Average fire resistance (mins)
W-W-W	Bolts 1	23.2	15	0.65	21.2	21.2
	Bolts 2	21.7	15	0.69	21.1	
S-W-S	Bolts1	11.5	7	0.61	9.9	9.2
	Bolts 2	11.3	6	0.53	8.4	
W-S-W	Bolts 1	19	11	0.58	15.5	16.3
	Bolts 2	19.5	12	0.62	17.0	
Mean char rate (mm/min)				0.65		

Table 3 Comparison of fire resistance between charring rate and fire severity correlation				
Connec-ions	Time failure (mins)	Fire resistance from charring rate (mins)	Fire resistance from fire severity correlation (mins)	Difference in fire resistance (mins)
W-W-W	22.5	21.2	20.5	0.7
S-W-S	11.4	9.2	8.8	0.4
W-S-W	19.3	16.3	16.5	- 0.2

König [7] states that for connections with side members of wood, ie. the W-W-W and W-S-W connections, fire resistance durations of 15 minutes for bolted connections is achievable. This can be seen to be in line in this research where the fire resistance of a W-W-W joint was found to be 20.9 minutes and that of a W-S-W joint to be 16.5 minutes.

Heated 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. 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. The temperatures ranged from ambient to 250°C

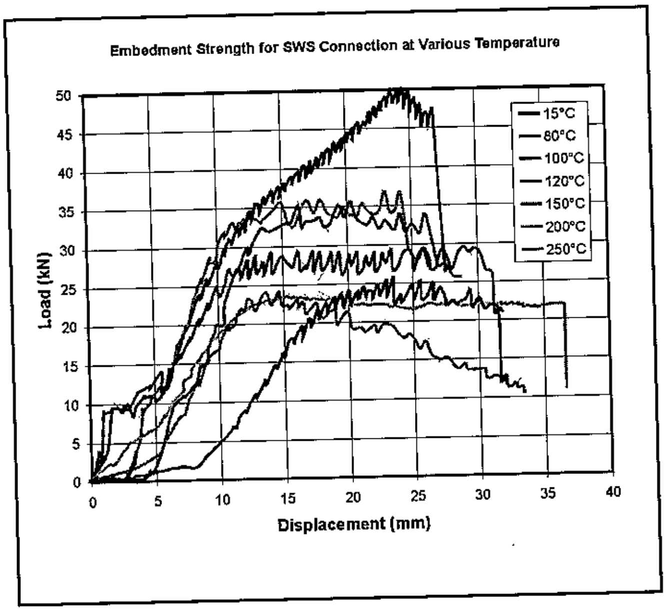

Figure 12 Load-displacement curves for bolted joints with a single bolt.

The test specimens were then quickly loaded to failure. Typical load-deflection plots at seven different temperatures are shown in Figure 12 for S-W-S joints. From these curves, a form of embedding strength can be determined from the maximum load, and the slope of the elastic region gives the stiffness.

The "embedding strength" is calculated by dividing the maximum load by the bolt diameter and the thickness of the member. In the future, these values will be used to calculate the joint strength at different temperatures using the European yield formulae in EC5 [8] which will be compared with the test results from the furnace testing.

Fire-protected connections

A number of tests were carried out on joints where the steel plates were protected by intumescent paint. In the S-W-S joints, the steel plates were painted with intumescent paint whereas in the W-S-W joints the gap between the steel plates and the LVL members was filled with the paint. As shown in Table 4, application of intumescent paint leads to a large increase in the fire resistance of the S-W-S joint. However, there is only a small increase for the W-S-W joint because the steel plates are already protected by timber side plates with only the edges being exposed to fire. A typical specimen before and after testing in the furnace is shown in Figure 13.

Table 4 Comparison of fire resistance between protected and unprotected connections

Connections	Fire resistance (min)		Increase in performance
	Unprotected	Protected	
S-W-S	8.8	18.7	112%
W-S-W	16.5	19.7	19%

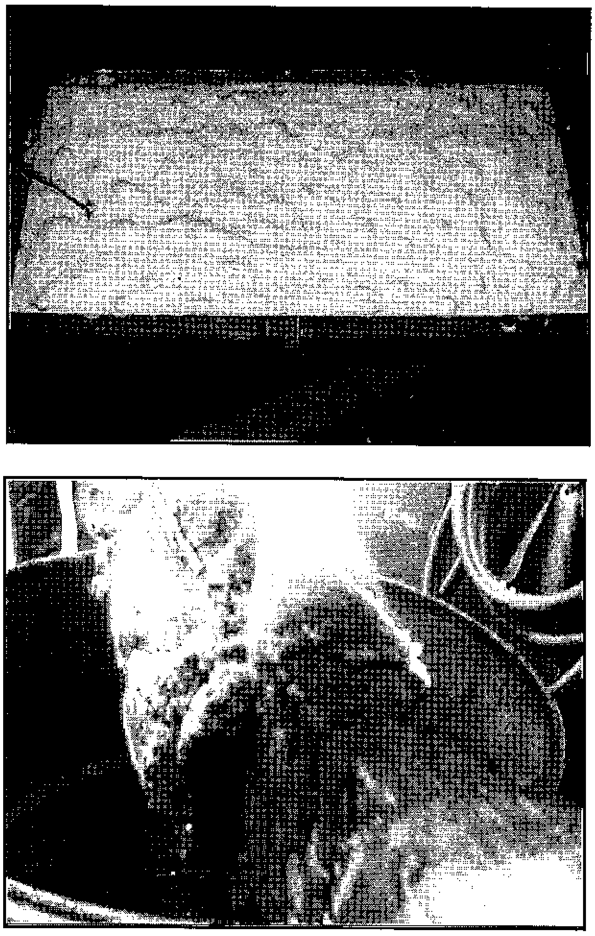

Figure 13 Before (top) and after (below) condition of S-W-S connection with intumescent paint.

The temperature measured on the bolt surface is shown in Figure 14 where it can be seen that fire protection on the steel plate significantly reduces the temperature in the bolt and consequently enables the joint to carry load for longer.

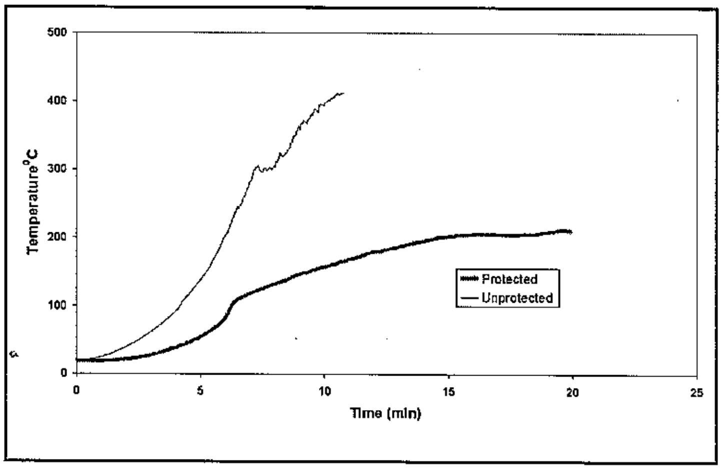

Figure 14 Temperature measured on the bolt surface in S-W-S connection.

Conclusions

- Of the three types of connection, the W-W-W and W-S-W connections had similar strength at ambient temperature. The S-W-S connections were found to have lower ultimate strength than the W-W-W and W-S-W connections.
- In the ambient tests, failure was caused by longitudinal splitting in the LVL at the bolt positions. A greater end distance could be used to increase the failure load, however this is unnecessary as the failure loads in all the tests were 100 – 200% higher than the design load in the New Zealand timber code.
- During furnace testing, the connections with mostly wood exposed to the fire (W-W-W and W-S-W) lasted much longer than those with large areas of exposed steel (S-W-S) where there was higher heat transfer into the connection via the steel side plates.
- The results from this non-standard furnace testing were converted to standard fire resistance times by two methods which gave similar results. One method was based on comparing measured char depths and the other was based on the "radiant exposure area correlation" concept.
- Intumescent protection increased the fire resistance of the connections, especially where large surfaces of steel were exposed to the fire.

Acknowledgements

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