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FULL-SCALE FIRE TESTS OF POST-TENSIONED TIMBER BEAMS

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ABSTRACT: This paper describes a series of full-scale furnace tests on loaded post tensioned LVL beams. Each beam was designed to exhibit a specific failure mechanism when exposed to the standard ISO834 fire. In addition to the beams a number of steel anchorage protection schemes were also investigated. These included wrapping the ends in kaowool, using intumescent paint, covering the anchorage with fire rated plasterboard and covering the anchorage with timber (LVL). The results of the full-scale tests cover temperature distributions through the timber members during the tests, the temperatures reached within the cavity and those of the tendons suspended within the cavity, the relaxation of the tendons during the test, the failure mechanisms experienced, and a summary of the anchorage protection details and their effectiveness. Recommendations for the design of both post-tensioned timber beams and associated anchorages are also provided.

KEYWORDS: Post Tensioned Timber Construction, Fire Performance, Furnace Test

1 INTRODUCTION

Whilst timber is the material of choice for the residential construction markets in New Zealand and Australia, the commercial markets are currently dominated by steel and concrete. Post-tensioned timber construction positions timber as a competitive alternative in the commercial building market, particularly in multi-storey and long-span industrial constructions. Post-tensioned timber construction has many benefits over steel and reinforced concrete; buildings can be constructed quickly, with substantially smaller lifting equipment, and timber has the added advantage of being sustainable and green, which is becoming increasingly important in the current economic climate [1, 2].

Post-tensioned timber construction (PT timber) is an adaptation of the mature technology of post-tensioned pre-stressed concrete construction for timber structures. PT timber is made with large timber cross sections, constructed from glue laminated timber (GLULAM) or laminated veneer lumber (LVL). The timber is post-tensioned with (unbonded) high strength steel bars or wire tendons which are run through a cavity within the member and fixed to steel anchorages at the end of the frame. The post-tensioning can be run through multiple bays of a frame at once and, when stressed, forms the primary beam-column connections. This means that many connections can be made at once. Figure 1 shows a 2/3rd scale post-tensioned timber frame used for seismic testing as part of research into post-tensioned timber at the University of Canterbury, New Zealand [3-6].

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Figure 1: 2/3rd scale post-tensioned structure for seismic testing research at the University of Canterbury

PT timber has many advantages over steel, concrete, and traditional timber. The post-tensioning reduces beam deflections and allows for smaller cross-sections to be used, in comparison to standard timber beams made from glue laminated timber or laminated veneer lumber. In seismic designs the post-tensioning serves to re-centre connections, eliminating residual displacement. Energy dissipation can be achieved with easily replaceable mild steel energy dissipaters. Also, as the mass of PT timber is much less than reinforced concrete, the forces the structure is exposed to would be much less, given a comparable acceleration [3, 4].

As with any timber construction there is a common perception of increased risk when exposed to fire, compared to incombustible materials such as concrete or steel. While the fire performance of heavy timber members is well established [7], the inclusion of a cavity within the timber member and the use of high strength steel tendons imply a loss of strength as a result of tendon relaxation due to temperature increases. The loss of cross-sectional area, due to charring, also results in an increased likelihood of shear and buckling failures of PT timber members. No full-scale tests of post tensioned timber members had been completed prior to this research.

In order to demonstrate the fire performance of post-tensioned timber members and to provide supporting data for the development of a fire design methodology a series of three full-scale fire tests were conducted on post-tensioned timber beams and fire protection details for their anchorages. This paper details the tests and their observations.

2 EXPERIMENTAL PROCEDURE

The tests were carried out at the Building Research Association of New Zealand's (BRANZ) fire testing facility in Wellington, New Zealand. The three beams fabricated from 63 mm LVL strips, span 4.4 m and were seated on a support frame placed over a standard fire test furnace of dimensions 4 m x 3 m and 1 m deep. The beams had a general cross-section as shown in Figure 2, which was then post-tensioned with steel wire tendons in the cavity. The fire test followed the ISO834 standard fire.

2.1 SETUP

To ensure that temperatures and pressures were maintained throughout the test furnace, an enclosure was built over the support frame and around the tested post-tensioned beam. In the first two tests, this was achieved by the use of gypsum plasterboard (GIB Fyreline), while a Hebel block wall with a precast concrete lid was used for the third test. Loads were applied to the test beams, using a pneumatic jack pushing against a removable reaction "A" frame. A spreader bar distributed the load to into two concentrated loads at 1.5 m spacing (Figure 3). To test the performance of protection materials for post-tension anchorages, unloaded short post-tensioned members were attached through the sides of the built enclosure (Figure 4). Gaps were sealed with kaowool or fire rated mastic.
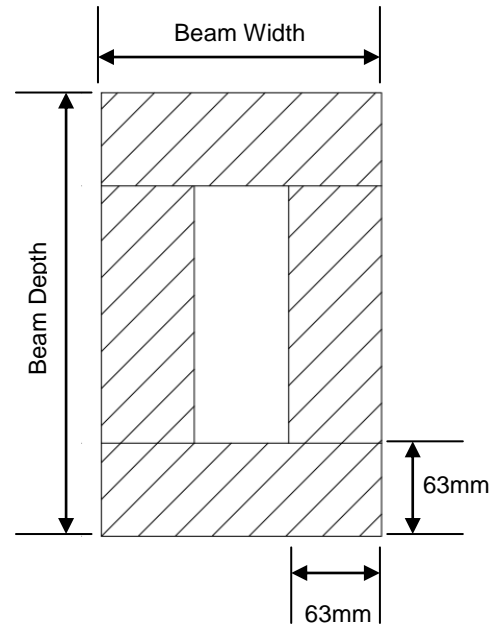

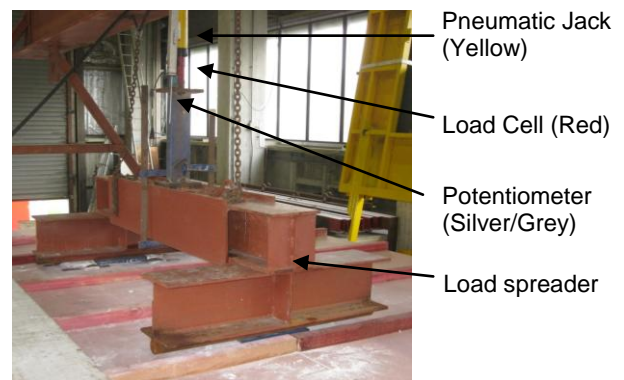Figure 2: beam cross-section dimensions

Figure 3: Load spreader bar, load cell, loading jack, and deflection potentiometer used during testing.
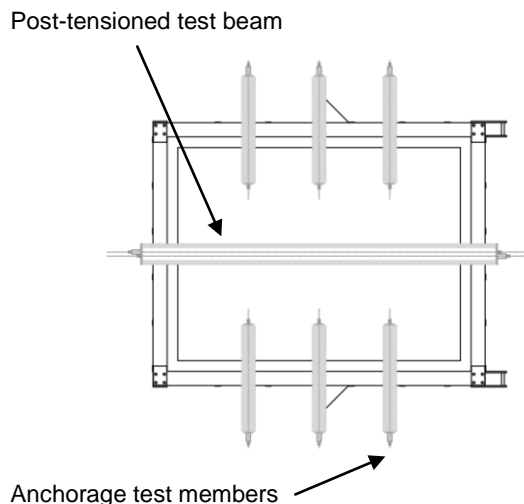

Figure 4: Typical test layout

To ensure that loads were applied directly to the tested beam, holes were cut in the roof of the enclosure, on top of the beam, and steel plates were placed within them to carry the loads from the spreader beam. Loading was by a computer-controlled pneumatic pump which provided a constant load throughout the test. Eight load cells were used to monitor the loss of post-tensioning forces in the tendons; two were placed on two tendons in the main beam, while the remaining six were placed on the anchorage test members. A load cell measured the total load applied to the beam while a potentiometer was used to measure the deflection of the beam under its load point.

2.1.1 Temperatures

K-type thermocouples were used to measure temperatures through the thickness of the timber. A number of thermocouple "plugs" were used. Each plug was 40mm in diameter and 58 mm long. Six holes were drilled into the plug for thermocouples to be placed in. A groove was also cut down the side of the plug to allow for the thermocouple wire. An orthographic drawing of a thermocouple plug is presented in Figure 5, and one of the plugs (before installation) is shown in Figure 6.
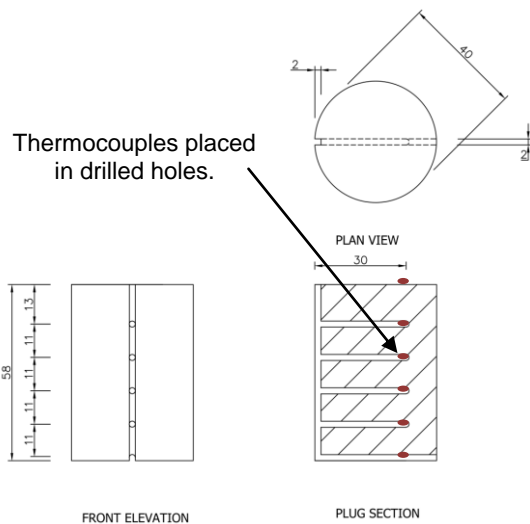

Figure 5: *Thermocouple-plug orthographic*

Figure 6: *Thermocouple plug and associated hole*

These plugs were glued into specially drilled holes in the webs and bottom flanges of each main test beam using the same resorcinol glue which was used in the fabrication of the beams. The holes were drilled with a 41 mm forstner bit which creates a flat bottomed hole. The holes needed to be drilled at the time of fabrication of the beams as there would be no access to the areas after the box beams had been glued together.

2.1.2 Thermocouple scheme

Thermocouples in the main beams were placed at three positions along the length of the beam: positions A, B and C. Position B is at the mid-span of the beam, position A is 1 m to the left of position B and position C is 1 m to the right, as illustrated in Figure 7 and Figure 8. A plug was placed in the bottom flange of each beam at positions A, B and C, in the left web in positions A and C, and in the right web in position B. A thermocouple was also placed in one of the lower corners of the beam cavity at positions A, B and C. Each tendon in the main beam specimens had a thermocouple attached at positions A, B and C.

In order to investigate the effect of the position of the tendon on the its temperature development, two 40 cm lengths of tendon were placed inside the first test beam specimen, with two thermocouples attached to each of them. The first was fixed to the centre of one web mid way between positions A and B inside the cavity. The second was suspended near the centre of the cavity between positions B and C.
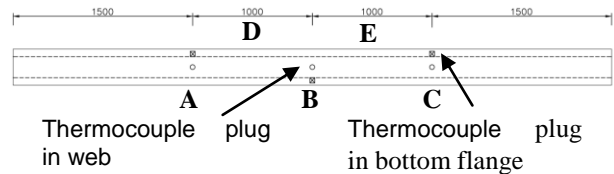

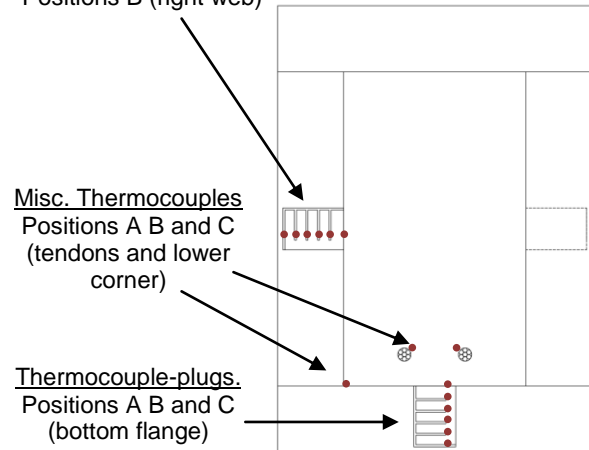**Figure 7:** *Temperature measurement positions in post-tensioned test beams.*

Figure 8: *Thermocouple-plug placement in cross-section*

2.1.3 Support assembly details

The GIB enclosure for Tests 1 and 2 was made from a 45mm square, rough sawn, radiata pine frame with studs at 450mm centres lined with two 13mm layers of GIB Fyreline, to provide a 60/60/60 minute fire rating [8]. A roof was made from the same timber and GIB boards. The lid rested on the beam in the centre and the stud wall around the perimeter of the test frame.

A Hebel block wall was used to create the enclosure for Test 3. Hebel blocks are a brand of aerated cement blocks made by Supercrete New Zealand. The aerated cement blocks were able to be easily cut with a hand saw, to create penetrations for the anchorage members. Two large precast concrete slabs were used as a lid for the Hebel block enclosure. These slabs left a 1m space in the centre where the main test specimen sat, which was then covered with 2 layers of 13 mm GIB Fyreline.

2.2 INDIVIDUAL TEST DETAILS

2.2.1 Test 1

Test 1 was a 426 mm deep and 300 mm wide box beam with 63mm thick webs and flanges. The tendons were stressed to a total post-tensioning force of 213 kN. Test 1 was expected to fail after 61 minutes of fire exposure with a shear failure in the bottom corner of the beam, as a result of the reduction of corner thickness due to corner rounding. The test included two Kaowool protected anchorages, two GIB board protected anchorages and two timber (LVL) protected anchorages.

2.2.2 Test 2

The Test 2 beam was 236 mm deep by 190 mm wide, constructed with 63mm LVL. Test 2 was initially estimated to fail with mid-span combined bending and compression at approximately 43 minutes, which was later revised to 37 minutes, after design revisions. The failure was expected to manifest as crushing in the top fibres. The tendons were stressed with an overall post-tensioning force of 214 kN. The test included two intumescent protected anchorages.

2.2.3 Test 3

Test 3 was designed after Test 2 failed prematurely. Its purpose was to demonstrate the bending and compression failure which Test 2 failed to show. The Test 3 beam was 300 mm deep by 190 mm wide, again constructed from 63 mm LVL. This beam was predicted to fail in combined mid-span bending and compression at approximately 53 minutes, due to combined bending and compression at the end of the beam due to the axial force and moment applied by the post-tensioning. The tendons were stressed with an overall post-tensioning force of 232 kN. The test included two intumescent protected anchorages and two unprotected anchorages.

2.3 FIRE TESTS

When failure occurred, indicated by runaway deflections, the furnace burners were stopped. The loading A-frame was unbolted and lifted off the furnace by an overhead crane while all load cells were unplugged and the thermocouple wires were cut. Once

the A-frame was clear of the test and the crane became available the test frame and specimen were lifted off the furnace and suspended above the workshop floor where they could be hosed down to cool the members and stop the charring and any continued burning. It took about 5-10 minutes from the end of the test till the test specimens could be hosed down. The specimen was then inspected. Once the specimens were cool enough to handle samples were cut from the beams for later analysis. Some of the anchorage test members, with various anchorage protection details, still had much of their post-tensioning stress at the end of the test, and required careful de-stressing. Figure 9 shows the A-frame over the loaded specimen during the fire test.

Figure 9: *Furnace during the testing of Test 1*

3 MATERIALS

Two main materials were used in the construction of the test specimens, Laminated veneer lumber (LVL), and steel wire tendons. Multiple other materials were used for anchorage protection. They included LVL, GIB Fyreline, Kaowool and Firepro PST-100 intumescent paint.

3.1 Laminated veneer lumber (LVL)

LVL is an engineered timber product consisting of a number of 3-4 mm thick veneers of timber which have been peeled from logs and glued together. The lamination of a number of layers causes defects to be spread through the beam which minimises strength loss due to knots or other defects. Also through manipulation of which veneers are used through the depth of the LVL the overall stiffness can be altered. Often the outer laminates have a higher stiffness and strength than the inner laminates. The veneers in LVL are oriented so that the grains run parallel to each other, unlike in plywood in which the veneer orientation alternates between layers. Plywood utilises the alternating orientation to provide bending resistance in two directions. LVL is usually used in applications where bending in one direction is required. There is however cross banded LVL, where some veneers are oriented at 90° to the others, to provide greater bearing or shear resistance. The LVL used in the manufacturing of these test specimens described in Section 2 was Carter Holt Harvey LVL13. Table 1 lists its properties [9].

Property		Value
Modulus of Elasticity	**E**	13.2 GPa
Bending strength	**f$_b$**	48 MPa
Tension strength	**f$_t$**	33 MPa
Compression strength	**f$_c$**	45 MPa
Shear strength	**f$_s$**	5.3 MPa
Density	**ρ**	620 kg/m^3
Veneer thickness		3-4 mm
Adhesive type		Type A phenolic
Char rate	**β**	0.72 mm/min 0.65mm/min +7mm

3.2 Post-tensioning Tendons

The tendons used for these tests were 12.7 mm nominal diameter, 7-wire strand (Figure 10), as used in post-tensioned concrete systems. Likewise, the barrel and wedge anchorage system was developed for application is post-tensioned concrete. The anchorages and tendons were supplied by BBR Contech. Tendon properties are listed in Table 2.

Figure 10: Post-tensioning tendon, and barrel and wedge system used for full scale testing

Table 2: Tendon Properties – BBR Post-tensioning Design Data

Properties		Values
MoE	**E**	180-205 GPA
Steel Area	**A$_s$**	100.1 mm^2
Nominal Diameter	**ϴ**	12.7 mm
Linear Mass	**m$_L$**	0.768 kg/m
Maximum Breaking Force	**MBF**	184 kN
Maximum Jacking Force	**MJF**	80% MBF

3.3 Fire Protection Materials

The following materials were tested as fire protection for post-tensioning anchorages in fire. An enclosure was constructed around the test anchorages with GIB Fyreline and LVL. Kaowool was wrapped around the anchorages and stapled to the timber, and the intumescent paint was painted onto the anchorages by hand.

3.3.1 GIB Fyreline

GIB plaster board is a brand of plasterboard manufactured by Winstone Wallboards Ltd. in New Zealand. The sheets of plasterboard are made from gypsum based plaster slurry rolled flat and lined with paper. The Fyreline product line uses additives and glass fibres within the gypsum to give some additional fire resistance. The manufacturer recommends 2 layers of 13mm GIB Fyreline board for a one way wall system to achieve a 60 minute fire rating. [8]

3.3.2 Kaowool

Kaowool is a ceramic fibre insulation material. The fibres are made from blown alumino-silicate. The material provides good temperature insulation and remains continuously stable up to temperatures of 1200°C. It is also chemically inert and has a good resistance to chemical attack. Thermal properties for Kaowool blanket are presented in Table 3. [10]

Table 3: Kaowool thermal properties [10]

Thermal Properties		Values
Specific Heat	**c$_p$**	1.13 kJ/kgK
Bulk Density	**ρ**	128 kg/m^3
Conductivity (600°C)	**k**	0.13 W/mK

3.3.3 Firepro PST-100 intumescent paint

The intumescent paint used in these tests was Firepro PST-100, which is a water-based intumescent paint used for fire protection of steel members. The intumescent system requires a primer coat and an acrylic top coat for durability and a good standard of finish. Due to the intumescent market being very proprietary, the actual material properties are unknown. The manufacturer recommends a dry film thickness of 1mm which can be achieved with 3 brushed-on coats. It should be noted that this recommendation is based on a critical steel temperature of 550°C which is unlikely to be appropriate for a post-tensioning anchorage as post-tensioning may be affected at a substantially lower temperature than structural steel.

3.3.4 Timber fire protection

The 63mm thick LVL timber used in construction of the beams was also used as a protection material for anchorages.

4 RESULTS

4.1 Thermal results

4.1.1 Timber temperature-time distribution

The temperature profiles of each beam did not vary significantly. During exposure to the ISO834 fire the

temperature at the exposed surface of the timber followed the random variations in the furnace temperature closely. Further into the section this became less evident and the curves became comparatively smoother.

Beneath the surface, the temperatures slowly approached 100 °C slowly and rapidly increased in temperature after 100°C was reached, most likely due to moisture migration and evaporation in the timber.

The bottom flanges heated slightly more quickly than the webs. Two possible explanations for this are that the flange partially shields the web from some of the furnace and therefore receives more radiation, or that the width of the beam became small enough that the two-dimensional heat transfer served to increase the temperature more quickly.

The temperature of the inside face of the LVL did not rise beyond 100°C whilst the beams were still intact. The temperature distribution of the web at various times for the beam in Test 1 is presented in Figure 11. This was typical for all tests.
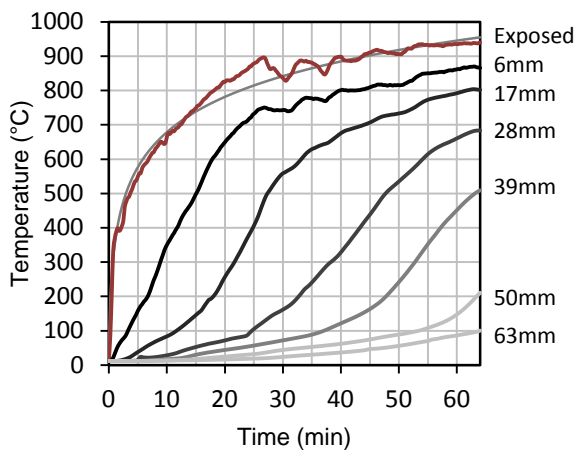
Figure 11: LVL temperature distribution in web of Test 1. Temperatures are presented for various depths below the original LVL surface.

4.1.2 Tendon Temperatures

As the timber sections charred, the inside face of the section became warmer. The tendon within the cavity also increased in temperature. In none of the experiments did the tendons nor the interior internal timber surfaces become hotter than 100°C before failure. In Test 1 the timber surfaces reached 100°C at 64 minutes just before failure whereas the tendon had only reached 75°C. After 45 minutes the internal timber surface was approximately 25-30°C hotter than the tendon. However the tendon temperature may have partially caught up with the timber temperature if the test progressed longer than 64 minutes. The temperature of the internal surface and the tendon are presented in Figure 12.
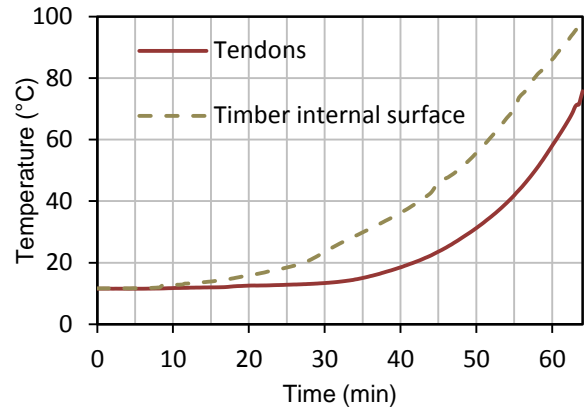
Figure 12: Average temperature of the post-tensioning tendon and the internal surface of the timber cavity of Test 1. Internal surface profile presented as recorded in the lower corner of the cavity.

4.1.3 Tendon position within a cavity

The position of the tendon within the cavity in Test 1 showed little effect on its temperature. The positions, near the bottom flange, near the web and near the centre of the cavity, showed a maximum temperature difference of 2 °C. The temperature profiles for the tendon at various positions are presented in Figure 13.
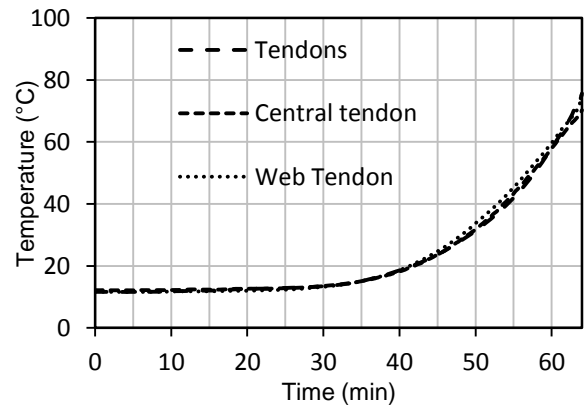
Figure 13: Temperature profiles for different tendon positions.

4.2 Tendon post-tension force and relaxation

Over the course of each test the post-tensioning force decreased with time due to heating, subsequent thermal expansion and loss of stiffness. Also the loss of the timber cross-section resulted in a reduced overall stiffness. Whilst the tendon force decreased with an increase of tendon temperature, there were other losses in stress which the increase in temperature alone did not account for. In later analysis it is shown that the beam geometry and deflection also affects the tendon force. End rotations and beam compression account for some of the increased loss in force. This is presented in a paper to be published [11].

During Test 1 the tendons had lost approximately 25% of their initial applied stress at 60 minutes. At this time the tendon temperature was approximately 58°C. Before 30 minutes of fire exposure both the temperature and

post-tensioning force were only negligibly affected by the fire. Figure 14 shows the tendon force and temperature of the tendons within the beam in Test 1.
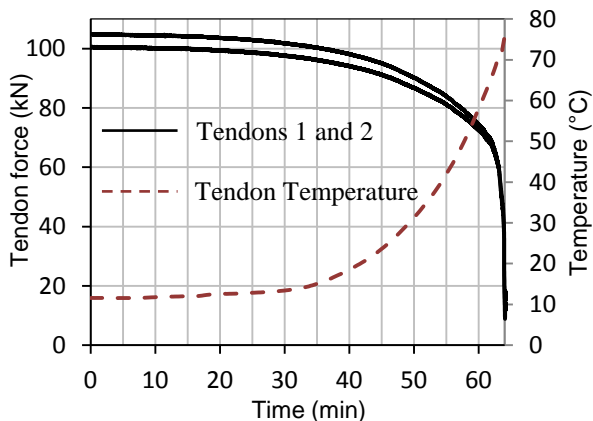

Figure 14: *Tendon post-tensioning force and tendon temperature during Test 1.*

4.3 Displacements

During Test 1 the deflections remained in the order of 0.5 mm-1 mm for the first 45 minutes. Beyond this the deflections started to increase steadily until approximately 64 minutes, where a runaway deflection occurred. The deflections measured during each test are presented in Figure 15.

During Test 2 the deflections increased at an approximately constant rate for 15 minutes, and then increased slightly until failure at 22 minutes. The mechanism of failure was different to what was predicted and occurred earlier than expected. The top flange suddenly disconnected from the rest of the beam. The deflection profile reflects this with rapidly increasing deflections early in the test.

The deflection profile during Test 3 was similar to Test 1. However, due to the beam being a smaller size, deflections were greater. The deflections increased approximately linearly for the first 40 minutes of the test. The rate of deflection then increased over the last 16 minutes of the test. At 56 minutes and approximately 30 mm of deflection the beam failed.
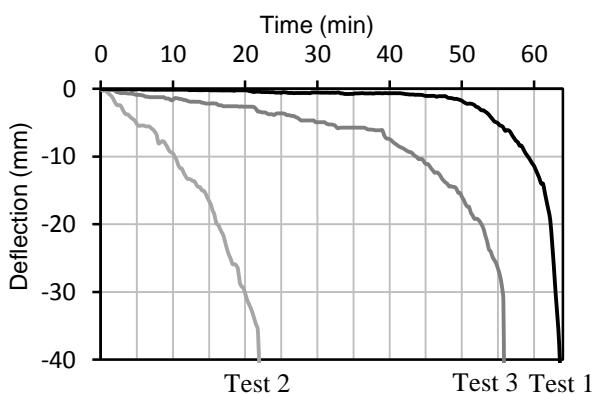

Figure 15: *Vertical deflections of the main test beams.*

4.4 Char rates

Due to the time involved in removing the loading frame, the beams continued to burn in the furnace for approximately 5-10 minutes before they were lifted off and cooled down. As the furnace was turned off, the exposed temperatures over the extra time were lower, implying slower charring. In order to include the effect of this extra time it has been assumed that the charring over the time is equivalent to 2 minutes charring at the assumed char rate. The measured charring rates (see Table 4) are close to the manufacturer's stated char rate. It should be noted that these char rates are sensitive to the above assumption and the addition of 2 minutes to the charring time.

Table 4: *Char rate results as measured from test specimens.*

Member	Char time (min)	Char Depth (mm)	Char rate (mm/min)	Corner rounding (mm)
Test 1	66	47.5	0.72	20-25
Test 2	25	18	0.72	20
Test 3	58	40	0.69	30

An estimated error can be calculated for the char rates. The depth measurement is accurate to ±1mm and the time is assumed to be accurate to approximately ±2 min. This inaccuracy in time is again due to the extra charring that occurred after the test had ended. The char depth inaccuracy is due to both the lack of a clear distinction between charred and un-charred timber and the random variation in depth across the surface of the timber. The error in the char rates for longer tests; Test 1 and Test 3, and anchorage members was between 5% and 6%. Whereas for the Test 2, which was substantially shorter, the char rate error was between 13% and 14%. The overall error was calculated as the sum of the relative errors of the charring time and the char depth. Because Test 2 was shorter and the char depth much smaller, the percentage of error is larger than for the longer tests. The char rates calculated from the 300°C isotherm are presented in Table 5.

Table 5: *Char rates results as calculated from the 300°C isotherm.*

	Char Depth (mm)	Char Rate (mm/min)
Test 1	39	0.74
Test 2	6	0.61
Test 3	28	0.61

The corner rounding was also measured, this however, was difficult to measure because it is not completely circular and its radius is open to interpretation, based on where measurements are taken. It was more accurate to use digital photography to fit circles to the charred corner profile. An example of the circles fit to the corner profile is shown in Figure 16.

Figure 16: Corner rounding radius fitting

The char rates shown in Table 4 are to the surface of the unburnt timber; however the timber below this layer is still substantially elevated. It was found that with the design methodology developed from these tests [11] the best correlation between predictions and results required the inclusion of an additional 7 mm zero strength layer beneath the char layer to account for the loss of strength and stiffness of the heat affected material. This 7 mm zero strength layer is suggested in Eurocode 5 part 2 [12] as one method to include temperature affected timber.

4.5 Failure Mechanisms

4.5.1 Test 1

A large portion of one end of the beam burnt through, as a direct result of the extra time it took to remove the loading frame. The remaining end showed two cracks in one of the webs. One crack ran along the bottom corner of the beam, where a shear failure had been predicted. The other crack was higher in the web approximately 3-5 cm below the top flange. Figure 17 shows the failure shape of in an un-deflected state. Figure 18 shows Test 1 after the beam had been removed from the furnace. The immediate aftermath of the test is shown in Figure 19.

Figure 17: Failure shape of Test 1

Figure 18: Test 1 beam after the test

Figure 19: Test 1 shortly after test

4.5.2 Test 2

Test 2 failed unexpectedly early. The top flange detached from the webs along most of the length of the beam. One end of the beam remained intact whereas at the other end the flange detached all the way to the end of the beam. The bottom section of the beam formed a channel which crushed near the mid-span of the beam, due to the post-tensioning compression and the compression due to bending. This formed a plastic hinge at the mid-span of the beam which meant only the weaker top flange was capable of carrying any load, causing the beam to fail. This plastic hinge resulted in localized buckling of the web, forcing the webs outward. Figure 20 and Figure 21 show Test 2 after failure. The premature failure of Test 2 led to design method improvements which incorporated the effect of axial loads on a deflected member more accurately.
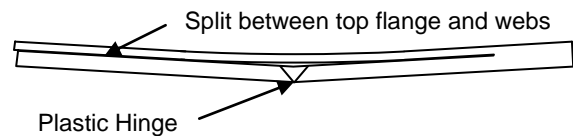

Figure 20: failure shape for Test 2

Figure 21: Test 2 beam after the test.

4.5.3 Test 3

Under one of the loading points in Test 3 a plastic hinge formed in the bottom channel of the section. This was again accompanied by a splitting of the web near the top flange. However, during this test the split was far more localized and did not split down the entire length of the beam. This plastic hinge exhibited some localized buckling in the web as shown in Figure 23.

A second plastic hinge formed near the vertical support closest to the bending failure. This point experienced no, or very low, bending moments due to the loading, however it did experience the maximum bending moment due to the post-tensioning. A hogging plastic hinge formed. Figure 22 and Figure 23 show the beam in Test 3 after failure.
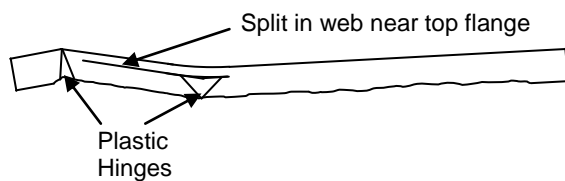

Figure 22: Failure shape of Test 3.

Figure 23: Test 3 beam after the test.

4.6 ANCHORAGE PROECTION

4.6.1 Unprotected anchorages

These heated quickly. The exposed side of the steel plate followed the temperature within the furnace quite closely. It took between 1 and 3 minutes for the average plate temperature to reach 200°C. The post-tensioning tendon maintained more than 95% of its initial post-tensioning force for 10 minutes after which the post-tensioning force decreased almost linearly. At 15 minutes the tendon had lost 50% of its original force.

4.6.2 Intumescent Protection

The intumescent protected plates heated more slowly than the unprotected anchorages. It took approximately 5 minutes for the average plate temperature to reach 200°C. The intumescent activated at approximately 3 minutes, corresponding to a steel plate surface temperature of approximately 100°C - 150 °C. The tendon again heated more slowly than the steel plate taking between 23 to 25 minutes to reach 200°C. The loss of 50% of the post-tensioning force again coincided

with the tendon temperature reaching 200°C which occurred at 15 minutes.

4.6.3 Kaowool blanket Protection

The anchorages protected with Kaowool blankets took between 32 and 37 minutes to reach an average plate temperature of 200°C. For most of the test the difference between temperature measurements on the anchorage were less than 100°C. The tendon reached a temperature of 200°C between 40 and 45 minutes. However, the tendon was did not lose 50% of its original force until at 63 minutes. The post-tensioning force remained above 90% of its original force for approximately 52 minutes.

4.6.4 Timber Protection

The timber protected anchorages performed well compared to the unprotected anchorage. The temperatures did not rise above 100°C during the 64 minutes of the test. The temperature stayed close to ambient temperature for approximately 35 minutes. It then rose steadily. The tendon retained above 60% of its original force for 60 minutes, after which its force dropped quickly.

4.6.5 GIB Board Protection

The GIB Fyreline protected anchorages performed well during the test, keeping temperatures below 200°C and not relaxing the post-tensioning force substantially. The temperatures of the anchorage quickly warmed to 100°C and remained there for most of the test. At approximately 55 minutes, the temperatures started to increase again. The post-tensioning force in the GIB board protected test did not drop below 85% of its original force.

5 CONCLUSIONS

A series of full scale furnace tests were conducted on three post-tensioned beams. During these tests five types of anchorage protection details were also tested. The full-scale tests successfully demonstrated the fire resistance of post-tensioned timber beams and also demonstrated potential failure mechanisms which will need to be considered during design. Test 1 successfully demonstrated a longitudinal shear failure in the lower corner of the cross section; charring at the bottom corners produce a cross-section that is too thin to carry the applied load.

Due to the increase in bending capacity as a result of the post-tensioning the tests did not show a combined bending and compression failure at mid-span. The post-tensioning moment and the short beam span made shear failure more likely to occur. However, Test 3 demonstrated a combined axial and bending failure at the end of the beam where, due to the changing cross-section, the post-tensioning moment and axial load caused a plastic hinge to form.

Test 2 failed earlier than expected. This led to improvements in the design approach. The design methodology before Test 2 did not sufficiently consider the additional moment due to the effect of axial loads on an already deflected beam.

Five different types of post-tensioning anchorage protection details were tested in the furnace, as a secondary objective, and useful information on each

method's fire protection potential was obtained. An unprotected anchorage retained its post-tensioning load for about 10 minutes. It was found that enclosing the anchorage in timber or GIB Fyreline provided the best protection. For timber protection, standard charring rate calculation methods could be used to determine the fire resistance rating. For GIB Fyreline the anchorage protection design should mimic the manufacturer's one-way fire wall system.

Intumescent paint protection and Kaowool protection were also investigated. These methods may work appropriately but more research is required. The Intumescent paint provided some protection but only for about 10 minutes more than an unprotected anchorage. Kaowool was an effective protection material but there are currently no simple design methodologies or thickness recommendations available for commercial use.

Based on these tests the following recommendations can be made:

- A minimum char rate of 0.72 mm/min should be used for New Zealand LVL. However, it is important to include an additional 7mm zero strength layer during design.
- During design of post-tensioned timber members it is important to consider the following failure mechanisms
    o Longitudinal shear failure in the webs near the centroid of the cross-section.
    o Longitudinal shear failure at any charred corner of the member.
    o Combined bending and compression failure at mid-span.
    o Combined bending and compression failure at the end of the beam due to the moments and axial loads induced by the post-tensioning.

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REFERENCES

[1] John, S.: Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials. 2008, MAF

[2] John, S., Perez, N., and Buchanan, A.H.: The Carbon Footprint of Multi-storey Timber Buildings Compared with Conventional Materials WCTE 2010, in *11th World Conference on Timber Engineering*. 2010: Riva del Garda, Trentino, Italy.

[3] Newcombe, M.: Seismic Design of Multistory Post-Tensioned Timber Buildings. 2007, University of Pavia: Pavia.

[4] Palermo, A., Pampanin, S., Buchanan, A., and Newcombe, M.: Seismic Design of Multi-storey Buildings using Laminated Veneer Lumber (LVL), in *Annual NZSEE Technical Conference*. 2005: Wairakei.

[5] Aalami, B.: Critical Milestones in Development of Post Tensioned Buildings. Concrete International, October, 2007: p. 52-56.

[6] Beerschoten, W.V., Palermo, A., Carradine, D., Sarti, F., and Buchanan, A.: Experimental Investigation on the Stiffness of Beam- Column Connections in Post Tensioned Timber Frames, in *Structural Engineers World Congress 2011*. 2011: Italy.

[7] Lane, W.P.: Ignition, Charring and Strucutral Performance of Laminated Veneer Lumber, in *Department of Civil Engineering*. 2005, University of Canterbury: Christchurch.

[8] GIB: GIB Fire Rated Systems, Winstonse Wallboards limited, Editor. 2006.

[9] CarterHoltHarvey Woodproducts New Zealand: hySPAN Span Tables for Residential Buildings, Edition 3. 2009.

[10] FORMAN building systems: KAOWOOL Product Data Sheet. 2002.

[11] Spellman, P.M., Abu, A.K., Carradine, D.M., Moss, P.J., and Buchanan, A.H.: Design of post-tensioned timber Beams for fire resistance, in *To be published in the 7th International Conference on Structures in Fire proceedings*. 2012: Zurich, Switzerland.

[12] British Standard Institute: Eurocode 5: Design of timber structures EN 1995-1:2004. 2004: U.K.