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Fire Performance of Gusset Connections in Glue-laminated Timber

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This paper describes a comprehensive experimental investigation of the fire performance of nailed gusset connections between large glue-laminated timber members. Both plywood and steel gusset plates were investigated with a range of loaded and unloaded test methods. The principal conclusions are that unprotected gussets have poor fire performance, but that a layer of solid wood or gypsum plasterboard will provide at least one hour of fire protection to typical joints.

INTRODUCTION

Because wood burns, timber buildings have traditionally had a poor reputation for fire safety. However, modern timber buildings can perform very well in fires, provided that they are designed correctly. This paper is concerned with the fire performance of the building structure (not the safety of occupants) in the early stages of fire growth.

Unprotected light timber framing loses strength rapidly in a fire but can be protected with gypsum plaster or similar non-combustible board material to achieve fire resistance ratings of up to 4 h. Heavy timber construction can perform very well in fire conditions because a char layer develops at a slow and predictable rate, protecting the residual timber core against premature collapse.

The fire performance of connections between glue-laminated timber members is less predictable. This paper describes a major investigation into the fire behaviour of nailed gusset connections.

Glue-laminated timber portal frame buildings of the type shown in Fig. 1 are popular in New Zealand and Australia, mainly for industrial and agricultural uses. They compete favourably with structural steel on both cost and speed and ease of construction. The gusset connections are usually steel or plywood gusset plates nailed to each face of the timber members. The structural glue-laminated members are generally of slender cross-section, providing a large face for nailing. These connections are particularly suitable for New Zealand-grown radiata pine which is able to tolerate the large number of nails required at close spacing without splitting.

Steel gusset plates (usually about 5 mm thick) are manufactured with pre-drilled holes for nails. The size of the steel gussets depend on the actions in the frame and the density of nails required. Two different styles are shown in Fig. 2.

Plywood gusset plates are often used as shown in Fig. 3, fixed with nails driven by nail gun. Plywood gussets are cheaper than steel but their use is limited by the maximum size of plywood sheets (1.2 × 2.4 m). If stresses in the plywood are critical, two sheets are glued together or composite gussets are used with a thin steel plate under the plywood.

These gussets are often used in industrial buildings not requiring structural fire resistance. If fire resistance is required, the glulam section properties after the specified period of fire exposure can be calculated and some form of protection can be applied to the gussets. Protection most often considered includes solid wood, plywood, gypsum plaster board, silicate board or intumescent paint. This study investigates the performance of these materials used on large moment-resisting gusset connections.

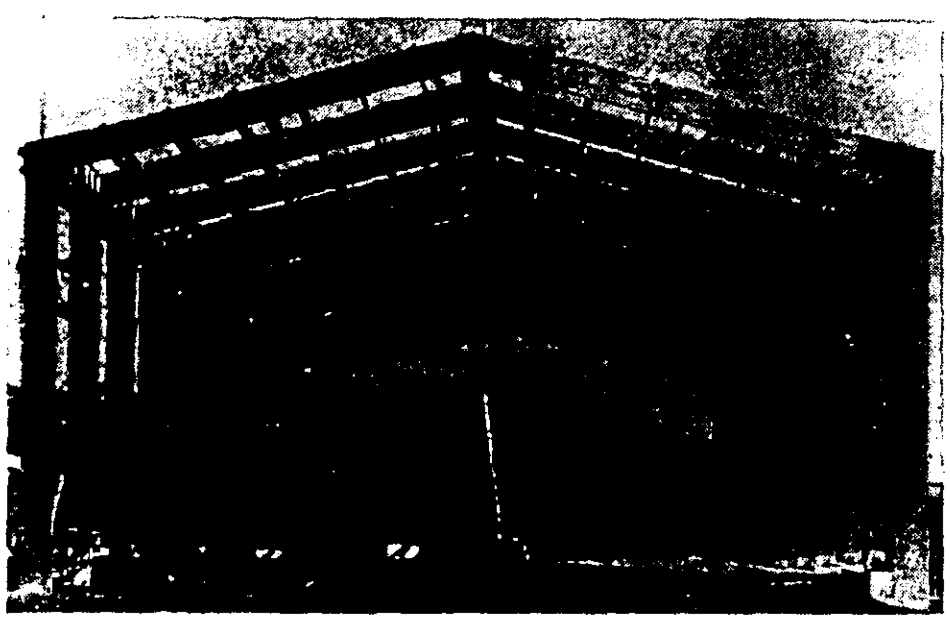

Figure 1. Glue-laminated portal frame building.

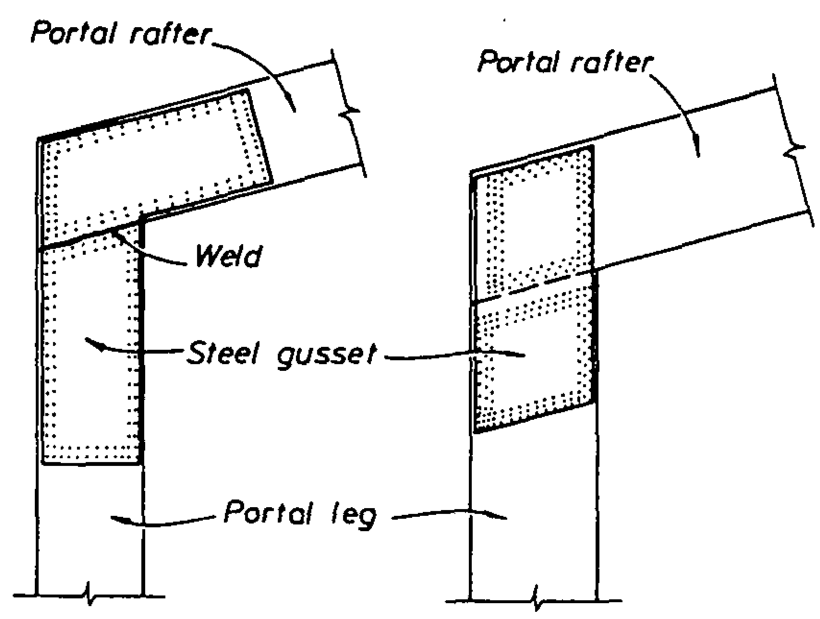

Figure 2. Steel gusset knee joints for portal frame buildings.

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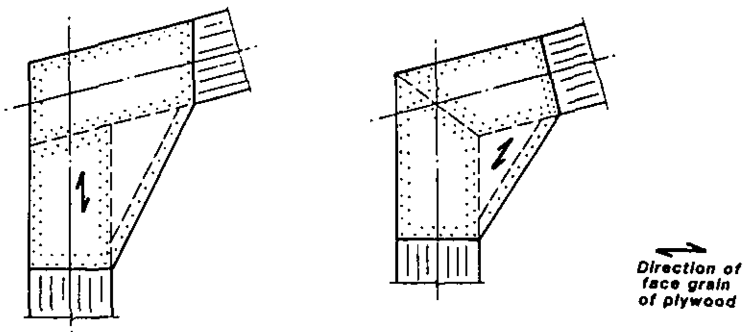


Figure 3. Plywood gusset knee joints for portal frame buildings.

PREVIOUS STUDIES

Connections

Many types of timber connections have been tested under fire conditions but there is no consistent test method and some results are inconclusive. A comprehensive survey of many tests is that by Carling.[1] Of these, the most relevant are those of Aarnio and Kallioniemi,[2,3] Rimstad,[4] Bakke,[5] Leicester *et al.*[6] and Hviid and Olesen,[7] all of whom tested nailed connections with exposed steel plates, both with and without insulation. They all found that charring occurs rapidly behind unprotected steel plates but temperatures can be controlled with various types of insulation.

A more recent survey concentrating on nailed gusset connections is that by Yiu and King,[8] who reviewed the above papers and many others, including Jackman[9] and Kordina and Meyer-Ottens.[10] Nailed timber gussets generally failed as a result of damage to the gusset itself or charring of the gusset around the nail heads, allowing them to pull through. Nail withdrawal from the main member did not appear to be a problem.

Charring

The charring rate of glue-laminated timber exposed to fire and the strength of the residual timber have been the subject of many studies, including Schaffer[11] and Fredlund[12] and others listed by Yiu and King.[8]

It is generally agreed that a reasonable design approach for large members is to assume a constant rate of charring, with no loss of strength of the wood in the residual cross-section. For smaller members it is important to consider more rapid charring at corners and the loss of strength of the layer of warm wood directly under the charred layer.

The New Zealand design code[13] permits the fire resistance of large timber members to be calculated using a specified charring rate of 0.6 mm min^{-1} on surfaces exposed to the fire, and this charring rate has been verified by Bastings.[14] Most codes use figures between 0.5 and 1.0 mm min^{-1}.

TESTING PROGRAMME

Four series of tests will be described, two series of unloaded pilot tests, one of loaded small-scale tests and one of loaded full-scale tests. The overall objective was to establish a suitable test method which could be used to assess the fire performance of alternative protection systems for gusset connections. A secondary objective was to investigate the type of protection necessary to achieve one hour of fire resistance for this type of joint.

All the timber and plywood was New Zealand grown radiata pine. The pilot and full-scale fire tests were carried out at the Building Research Association of New Zealand. Specimens were subjected to the ISO 834 fire exposure regime.[15] The loaded gusset tests were carried out at the University of Canterbury.

Pilot fire tests of unloaded gussets, one face exposed

This series of tests was carried out on unloaded blocks of glue-laminated timber with various forms of protection and with gusset plates attached to one surface. The tests are described in detail by Yiu and King.[8]

Test procedure The test specimens were blocks of glue-laminated timber (360 mm square) mounted in a concrete wall such that one face and part of four edges were exposed to the ISO 834 standard fire test in a pilot furnace, as shown in Fig. 4. The blocks were mounted as shown in Fig. 5 with a 5 mm thick steel or 18 mm thick plywood gusset plate attached to the fire-exposed face. These gussets were tested unprotected, and protected with layers of various materials.

Types of protection included solid wood, 40 mm thick, two layers of 18 mm thick plywood, paper-faced gypsum plaster board in one layer of 19 mm or two layers of

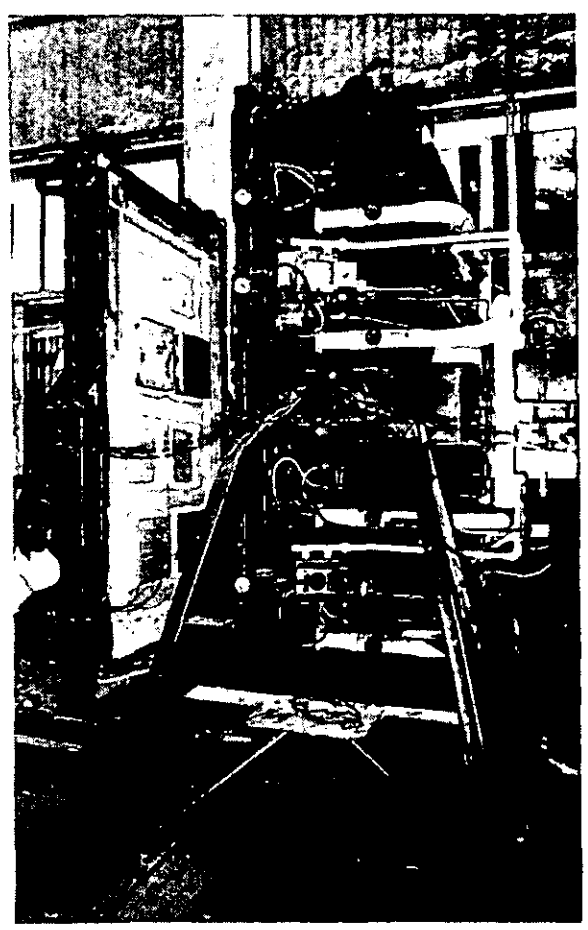


Figure 4. Pilot test set-up showing unloaded protected gusset specimens in test wall.

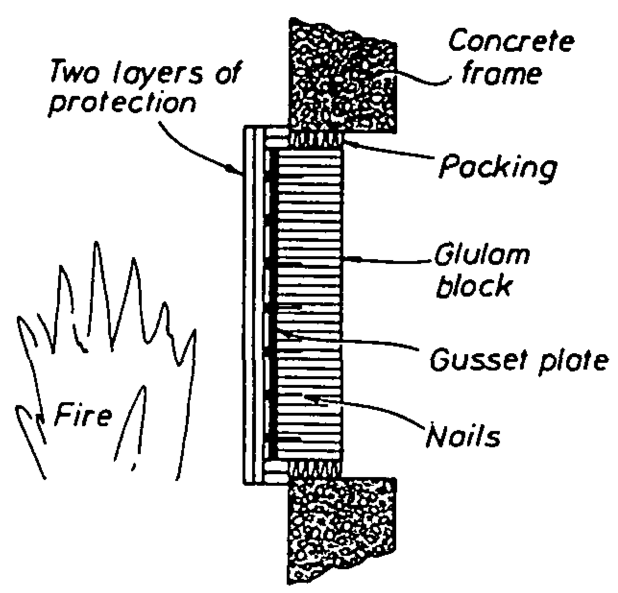


Figure 5. Cross-section through unloaded protected gusset specimen.

14.5 mm thickness, and intumescent paint (steel gusset only). The intumescent paint was Nullifire S60, 2200 g m^{-2}.

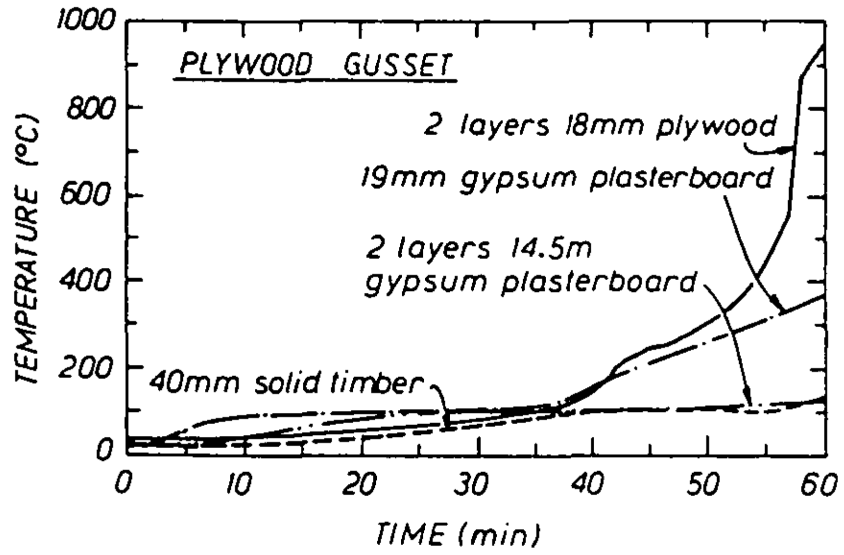
Results The gussets with no protection performed very poorly. The unprotected plywood gusset had disintegrated and fallen off after 43 min. The unprotected steel gusset heated rapidly, followed by charring of the timber which caused a gap between the steel and timber to occur after 25 min, growing to 10–15 mm after one hour.

The protected gussets performed much better, depending on the type of protection. Temperatures behind the protective layers are shown in Fig. 6. The solid wood protection remained in place for the full one-hour duration, although the outer surface was charred and fissured. Gusset temperatures remained low. The average charring rate of the solid wood protection was 0.65 mm min^{-1}.

The plywood was unsatisfactory as a protection material. Cracks rapidly developed in the outer veneer, leading to its disintegration and allowing the fire to attack the next layer. The deterioration was very rapid in the last 15 min of the test, as can be seen by the temperatures in Fig. 6.

The paper-faced gypsum plaster board provided good protection. There was some crumbling of the surface layer and some damage at the joints, such that the outer layer of board could be removed by hand at the end of the test. The temperatures (Fig. 6) show the characteristic temperature plateau at 100°C as water of crystalization is driven off. The plateau lasted for 35 min for the thin board and for the full test for the thicker board. The intumescent paint swelled and charred as expected, but temperatures reached 200°C after 10 min and continued to climb steadily, as shown in Fig. 6.

The conclusion drawn from these initial tests was that the gusset performance was solely related to the temperature increase in the gusset itself and the glulam member underneath. Both gypsum plaster and solid wood provided satisfactory protection but only gypsum plaster was used in the following series of tests.



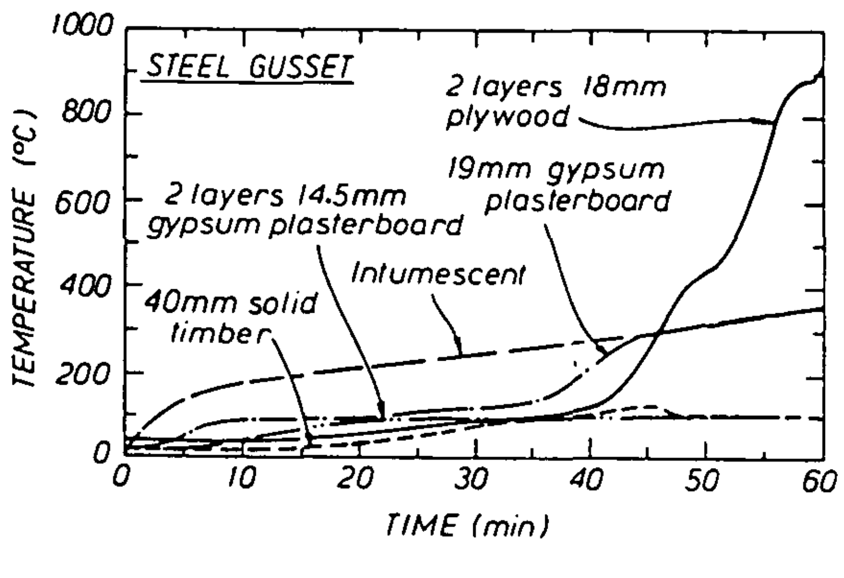


Figure 6. Temperatures measured behind the surface protection for plywood and steel gussets.

Simulated fire tests of loaded gussets

Simulated fire tests on loaded gussets were carried out to investigate the load-slip behaviour of nails in gusset plates, exposed to elevated temperatures. These tests are described by Chinniah.[16]

Test procedure Small steel and plywood gussets, approximately 200 mm square, were nailed to blocks of glue-laminated timber with six nails. The nails were loaded in shear with a constant load, as shown in Fig. 7, while the gusset was heated. The heat was applied with an electric element, controlled to induce the temperatures obtained in the unloaded tests shown in Fig. 6. A comparison of the heating conditions with the earlier tests is shown in Fig. 8.

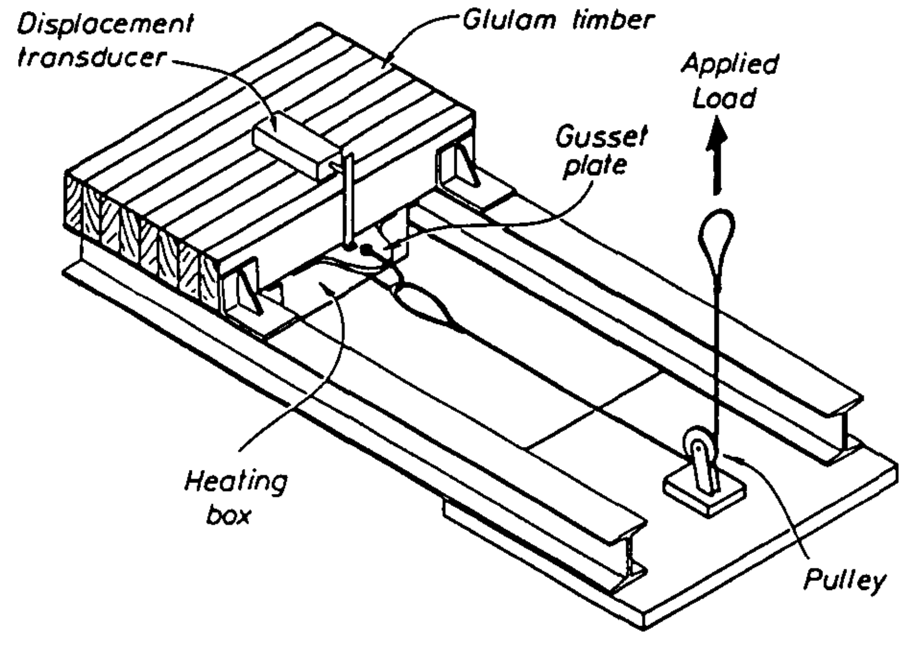


Figure 7. Testing arrangement showing steel gusset being tested.

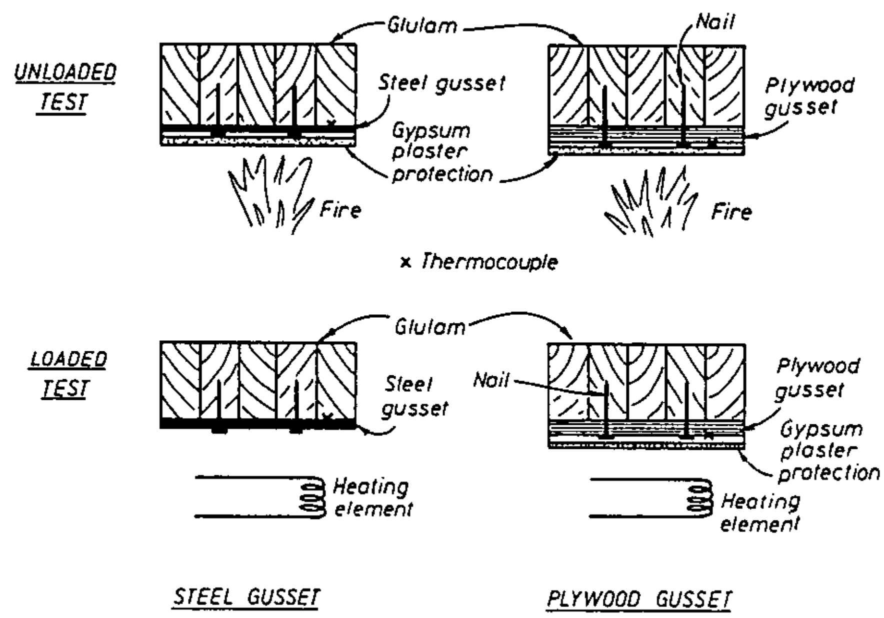


Figure 8. Comparison of heating conditions in unloaded and loaded tests.

Tests were carried out with different sizes of nails (from 40 to 75 mm long) and different load levels, both parallel and perpendicular to the grain, for both steel and plywood gussets. The loads varied from 0.1 to 1.0 kN per nail.

Results Displacements were plotted against time under constant load for all of the tests. Deflections after one hour were all less than 2 mm, much less for low load levels. A typical plot is shown in Fig. 9.

In order to calculate rotations in an actual joint where different nails carry different loads (due to the geometry of the joint), a load-displacement relationship is required. Such a relationship can be derived from Fig. 9 at any given time. For example, Fig. 10 shows the implied load displacement relationship after one hour of fire exposure. Points are plotted for both parallel and perpendicular to grain loading, with a fitted curve predicting average behaviour.

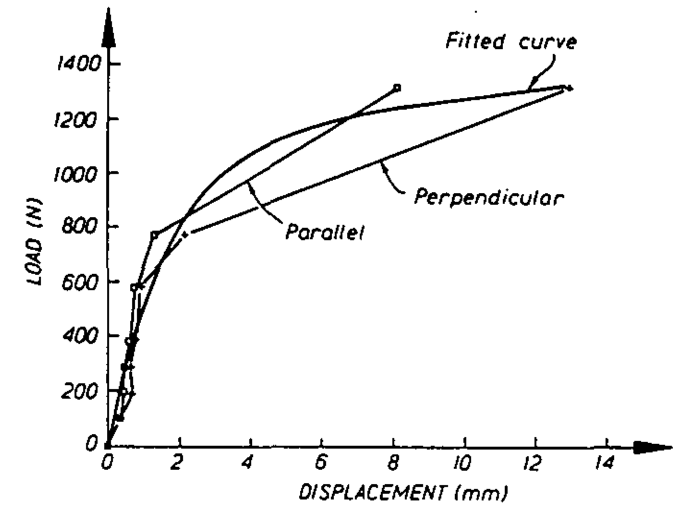


Figure 10. Load versus displacement relationship derived from displacement versus time graphs.

Full-scale fire tests of loaded beams

Tests were carried out on six full-size loaded beams with nailed gusset splices at midspan. The splices were designed to simulate portal frame knee connections. Test details are described by Lim and King.[17]

Test procedure The beam geometry and details of protection are described in Table 1 and Fig. 11. The 'control board' referred to in Table 1 was a paper-faced gypsum plaster board, 14.5 mm thick.

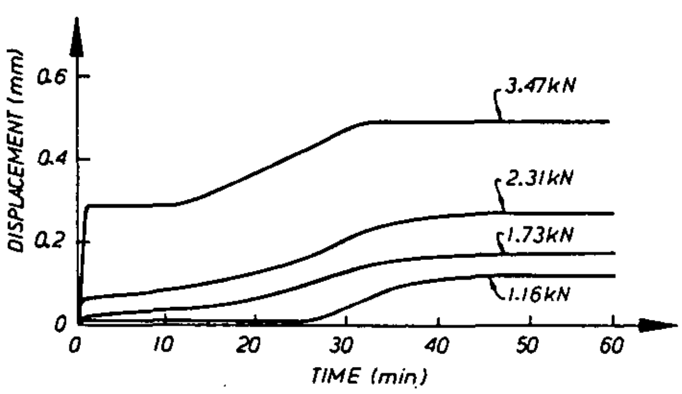


Figure 9. Displacement versus time for steel gusset with four load levels.

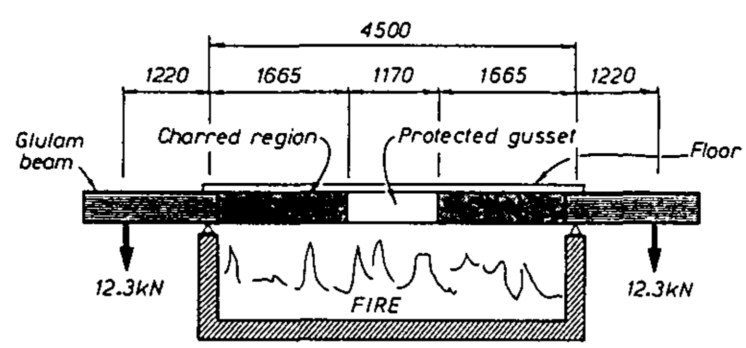


Figure 11. Test set-up for full-scale tests on loaded beams.

Table 1. Details of splices in full-scale beam tests

Beam ID	Type of protection	Gusset material	Beam depth (mm)	Nail load (x basic)	Applied moment (kN.m)	Member stress (MPa)
PG1	Two layers 'control' board (CB)	30 mm plywood	540	1.8	26	11.3
PG2	Two layers CB	30 mm plywood	540	1.2	17	7.4
PG4	Two layers CB	30 mm plywood	630	1.2	20	6.1
PG3	One layer CB	30 mm plywood	540	1.2	17	7.4
SG1	One layer CB	5 mm steel	540	1.2	15	6.5
SG2	Intumescent coating	5 mm steel	540	1.2	15	6.5

Three beams were tested at each firing in the 4 m × 3 m furnace. Each beam was subjected to constant bending moment along the fire-exposed length, with heavy weights hanging on the free ends of the beams outside the furnace. The first test was stopped after 50 min following failure of the central beam. The second test was run for 60 min, with the load removed from the central beam after 53 min. The beams were deemed to have failed if the midspan deflection exceeded 1/20 of the span or 1/30 of the span with an excessive rate of increase.

Results The two beams which failed under test (beams PG2 and SG2 in Table 1) both failed as a result of loss of cross-section some distance from the gusset splice. The other four beams all carried the applied loads for the duration of the test.

Although the average temperature regime in the furnace followed the ISO 834 curve as far as possible, with equivalent severities of 99% and 103%, there were significant differences in the response of the three beams in each test. In both cases the central beam charred more rapidly than the outer two, even though the temperatures in the central region were only marginally higher. The more rapid charring rate is thought to result from the more intense radiant heat transfer from the combustible surfaces of the adjacent beams. The average rate of charring on the outer faces of the two outer beams in each test was 0.84 mm min^{-1}. The average rate on all faces was 1.15 mm min^{-1}. These rates are much more rapid than those measured under similar temperature conditions in the earlier pilot tests.

The plywood gussets protected with two layers of gypsum plaster board performed very well. The surface of the plywood and the beam beneath were not charred after 50 min exposure. The maximum deflection was only 44 mm. The plywood and steel gussets protected with one layer of gypsum plaster board also performed well, although the temperatures were higher than for two layers, and the outer surface of the plywood gusset was charred 10–15 mm. Deflections were increasing rapidly towards the end of the test, indicating that there was not much reserve strength after 60 min.

In all tests the temperatures under the protection were higher than those measured in the unloaded tests.[8] This difference is attributed to the full immersion of the specimen in the furnace and radiant heat transfer from the adjacent beams compared with one-sided exposure in the pilot test.

There was little difference between the performance of the steel and plywood gussets under similar circumstances. Temperatures were a little higher under the steel gusset, but rotations were a little greater for the plywood one, attributed to some softening of the plywood at elevated temperatures.

The performance of the intumescent coating on steel gussets was inconclusive. This specimen failed at 52 min due to charring of the beam, but rotations within the connection region were increasing rapidly at this time and inspection after the test showed severe charring under the gusset and along the unprotected underside of the beam. The intumescent coating provided some protection but insufficient to ensure one hour of fire resistance.

Pilot fire tests of unloaded gussets, both faces exposed

Because of the higher than expected temperatures in the full-scale fire tests described above, a further series of unloaded pilot tests were carried out to confirm gusset temperatures under one layer of gypsum plaster board protective material. These tests are also described by Lim and King.[17]

Test procedure The test specimen consisted of a short length of 540 mm × 135 mm glue-laminated timber projecting 500 mm into the pilot furnace, as shown in Fig. 12. Each beam had a gusset plate nailed each side, with protective material applied. This type of specimen was used in an attempt to simulate the exposure of the full-scale tests in the pilot furnace.

Results The temperature readings obtained in these tests showed results similar to those in the full-scale loaded tests. This indicates that the full-scale tests can be simulated in the pilot furnace, and for the narrow beams used in this study, two-sided exposure is more severe than one-sided exposure. The results of these tests have been used as the basis of a Technical Recommendation[18] for evaluating the fire performance of other types of protection using unloaded test specimens of this type.

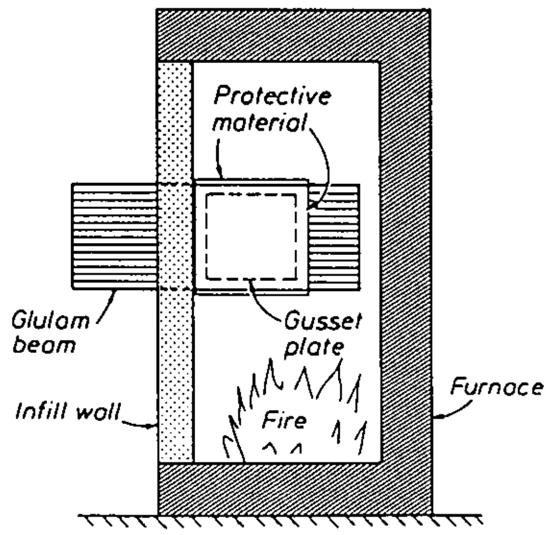


Figure 12. Cross-section through pilot furnace, showing revised detail for testing unloaded specimens.

CASE STUDY

As an application of the results of this study, a simple portal frame building (of the type shown in Fig. 1) was analysed for one hour of fire exposure.[16] The building has 585 mm × 135 mm glue-laminated timber three-pinned portal frames at 6.5 m centres, spanning 18 m. Initial design is for dead load plus snow load. A bending moment diagram is shown in Fig. 13. The roof is assumed to be of fire-resistant construction so that it remains in place for the duration of the fire.

The glue-laminated timber cross-section before and after the fire is shown in Fig. 14. The residual section has just sufficient strength to resist the moments from dead load only, given the increases in permissible stress allowed in the code.[13] The roof is assumed to provide sufficient lateral stability.

The number of nails in the connections were calculated using the method described by Walford.[19] Connection rotations are calculated under both cold and fire conditions for both steel and plywood gussets, using a load displacement relationship of the type shown in Fig. 10 to develop a moment-rotation relationship for each connection. These calculations show that for steel or plywood gusset plates protected with one 19 mm layer of gypsum plaster board the connections are strong enough to carry the applied loads under fire conditions until critical stresses are reached in the charred glue-laminated timber away from the connection.

Frame deflections due to connection rotations are small, similar to those under dead load on the original frame. Under fire conditions much larger frame deflections result from the reduced cross-section of the main members.

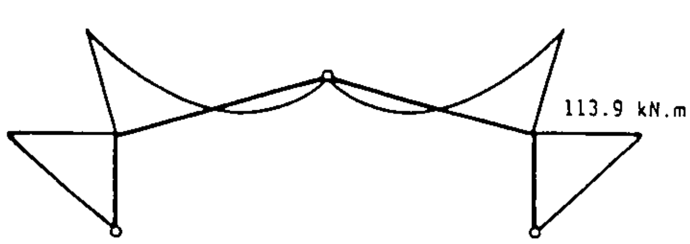


Figure 13. Bending moment diagram for portal frame.

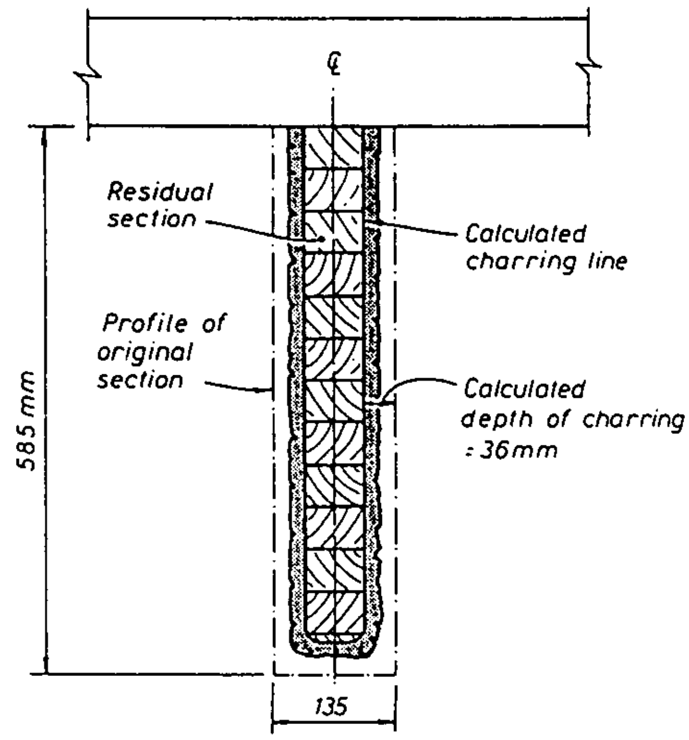


Figure 14. Cross-section of glulam beam before and after one hour of fire exposure.

CONCLUSIONS

Performance of gussets

Moment-resisting connections between glue-laminated timber members can be made easily with both steel and plywood gussets of various geometry. These gusset connections have excellent fire resistance of one hour or more when suitably protected. Unprotected gussets have poor fire performance. When proper protection is applied to the connections the loss of strength of the main members due to charring is more important than any loss of strength in the connection. This test series shows that protective materials for nailed gusset connections can be assessed in pilot-scale unloaded tests provided that representative details are tested.

Comparison of protection materials

The gypsum plaster board used in these tests provided excellent protection. The formulation of the board and fixing to the connection must be such that it remains intact throughout the fire exposure. The water of crystallization in gypsum plaster provides a heat sink which delays temperature rise.

Solid timber protection performed well in unloaded pilot tests but was not tested in full-scale tests. Plywood performed poorly as a protection material. It deteriorated under fire attack at a much faster rate than the equivalent thickness of solid wood. The sacrificial char method of calculating fire performance should not be used with plywood. Intumescent paint on steel gussets provided some protection but the results were inconclusive. As used in these tests, the intumescent paint did not achieve one hour of fire resistance, but more testing is necessary.

Acknowledgements

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