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The Fire Behaviour of Protected Unloaded Gusset Connections for Glulam Timber Members

A.B. King and P.K.A. Yiu

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The Fire Behaviour of Protected Unloaded Gusset Connections for Glulam Timber Members

A.B. KING
Leader Structural Engineering Section BRANZ
P.K.A. YIU
Former Research Engineer BRANZ

SUMMARY This paper discusses a series of experimental pilot fire tests which examined the behaviour of nail-on gusset plates on glued laminated (glulam) timber specimens. An initial comparison of the behaviour of laminated timber block specimens was undertaken. Subsequently specimens were tested where the gusset was unprotected and others where the gussets were protected with various forms of passive protection. The paper concludes that the fire behaviour of the glulam specimen was similar to that of natural timber, and that unprotected gusset connections are unsatisfactory during fire attack, while protected gussets can achieve a fire resistance rating similar to that of the member itself.

1 INTRODUCTION

1.1 General

In New Zealand, increasing popularity of timber constructions and the versatile nature of glued laminated (glulam) members have resulted in 'heavy' (>75 mm thick) timber structures becoming more varied in their uses. The performance of 'heavy' timber structures in fire is commonly accepted and acknowledged as an advantage in such constructions. The design of these members is based on the method of "sacrificial char". This method accepts that charring will occur and requires that the residual section will be sufficient to perform the load-carrying function of the member.

However, as in other structures, there exists the problem of connections where metal or timber components are involved. Steel components frequently used as connectors are good conductors, and readily transmit heat to any timber components they contact. Charring of this timber will result. Bolts, screws or nails similarly provide a heat path into the timber. This may result in local charring with subsequent loss of anchorage of the fixing or rigidity of the joint.

A common building system used for low-rise industrial structures (one or two storey) incorporates portal frames with moment-resisting connections consisting of nail-on steel or plywood gussets. To maximise the site usage, these structures are frequently built up to, or close to one or more boundaries, and are therefore required to achieve a one hour fire resistance rating (FRR).

This paper reports on the first phase of research undertaken at the Building Research Association of New Zealand (BRANZ) into the fire behaviour of glulam timber members and appropriate means of protecting gusset connections of such members. The results of this study form the basis for further work into the effects of loading, scale and suitable methods of protection.

1.2 Types and Forms of Protection

The provision of a passive form of fire protection to joints has been accepted by the design profession. Such systems insulate and shield the connection or the critical component from the fire as well as reducing the oxygen supply to combustible components (e.g., the glulam member).

Common protections include one or more of the following:

(1) Sacrificial or non-combustible boards or specially moulded encasements, e.g., timber, plywood, gypsum plaster, mineral fibre and fibreglass-reinforced plaster.

(2) Fire retardant plasters, e.g., gypsum-vermiculite or gypsum-perlite.

(3) Fire retardant coatings, e.g., mineral wool fibres or intumescent coatings.

Several overseas studies on various joint geometries have been undertaken (Carling, O. 1986 and Aarnio and Kallioniemi 1983). The general conclusion from these studies is that, with suitable protection, a one hour fire resistance can be achieved. However, the geometry of the joints studied was quite different from the large nail-on gusset side plates frequently used in New Zealand portals, where a capacity design approach is preferred to satisfy the earthquake provisions. Following a philosophy similar to that outlined in the above studies, passive protection of the joint seemed a reasonable approach for these gusset systems.

1.3 Design and Failure Criteria

Overseas Standards, (e.g., BS 5268:Part 4 (1978), NS 3478 (1981), DIN 4102:Part 4 (1981)) specify various criteria for the design or failure of unprotected connections or the protection requirements. The general trend however is to provide passive protection to the exposed face of the joint thereby ensuring that the temperature of the timber adjacent to the joint is maintained below that which will damage the timber. NS 3478 quantifies this temperature as 300°C. Other standards such as BS 5268:part 4 and DIN 4102:part 4 specify the type and thickness of the protection that is required.

The failure criteria, where identified, are usually a function of strength, deformation and temperature, all of which are interrelated. For strength, the connection is required to sustain the highest working load expected during the fire attack such that the structural performance is retained for the required duration. It is frequently the relaxation of the joint which occurs as a result of large local deformations within the timber-gusset contact areas which dictates the performance of gusset joints (Ahlen and Mansson, 1979; Jackman, 1981). For the structural frame, AS 1530.4 (1985) specifies as a failure criteria that the vertical deflection of roof or roof-ceiling systems should be less than one-thirtieth of the clear span, this being based on observation of deflection related to eventual collapse. The onset of charring, acknowledged to occur at approximately 300°C, is frequently the temperature control imposed.

2 The Experimental Programme

The aim of this series of pilot tests was to examine the fire characteristics of natural and glulam timber and the behaviour of both protected and unprotected gusset connections under fire attack in order to identify critical design parameters. All glulam specimens were fabricated from No.1 framing grade Pinus radiata timber.

2.1 Block tests: These preliminary tests was undertaken to compare the fire behaviour of glulam with that of natural timber, and the effectiveness of different methods of fixing boards to the specimen. A natural and a glulam specimen were tested. Each was 90 mm thick and had half their depth exposed to the furnace (Figure 1a). These formed the control tests for the series. Three glulam specimens were cut vertically (across the laminations) to form a 45 mm thick block and two 22.5 mm thick off-cut plates. The offcut plates were then laminated back onto the block (Figure 1b). One specimen was nail laminated, one was glued laminated and the third nailed and glued. A final specimen was cut vertically and three layers of 14.5mm paper faced gypsum plaster board nailed and glued to the cut face (Figure 1c).

2.2 Unprotected gussets: One glulam specimen with a plywood gusset and a second with a steel gusset were tested (Figure 1d). Thermocouples were attached to measure the timber surface temperatures as well as the nail tip temperatures.

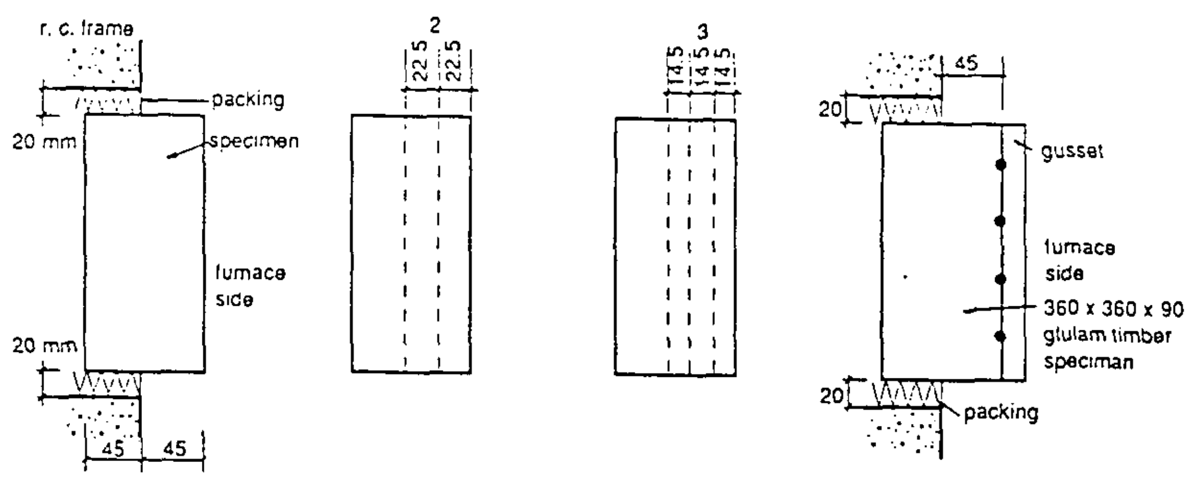
2.3 Protected gussets: a total of seven glulam specimens with protection were tested. The configuration and protective material varied. These comprised specimens with the following configuration (as shown in Figure 2) and protection:

(i) 40mm thick solid timber to configuration A
(ii) 2 layers of 18 mm thick plywood to configuration A
(iii) 2 layers of 18 mm thick plywood to configuration B
(iv) 19 mm thick paper-faced gypsum plasterboard to configuration A
(v) 19 mm thick paper-faced gypsum plasterboard to configuration A
(vi) 2 layers of 14.5 mm thick paper-faced gypsum plasterboard to configuration A
(vii) Intumescent coating applied at 2200 grams per square metre to configuration C.

Protection configuration A simulated the condition where the connection was protected on all sides. For configuration B the protection was provided on the gusset surface only and the gussets and the nails were set back from the edges of the timber by the notional charring depth.

The tests were conducted at the BRANZ Fire Laboratory at Judgeford. Up to six 360 x 360 mm and two 180 x 180 mm specimens were able to be mounted into a reinforced concrete panel with suitable openings such that they were exposed on one face and to mid-depth. The panel was mounted vertically and sealed onto the face of the 2.2 m high by 1 m wide oil-fired pilot furnace, and the temperature conditions controlled with time as specified in ISO 834 (1975).

The tests were terminated after the specimens had been exposed to the test fire for 60 minutes.



1 (a) Configuration of solid blocks

1 (b) Configuration of relaminated specimens

1 (c) Configuration of protected specimens

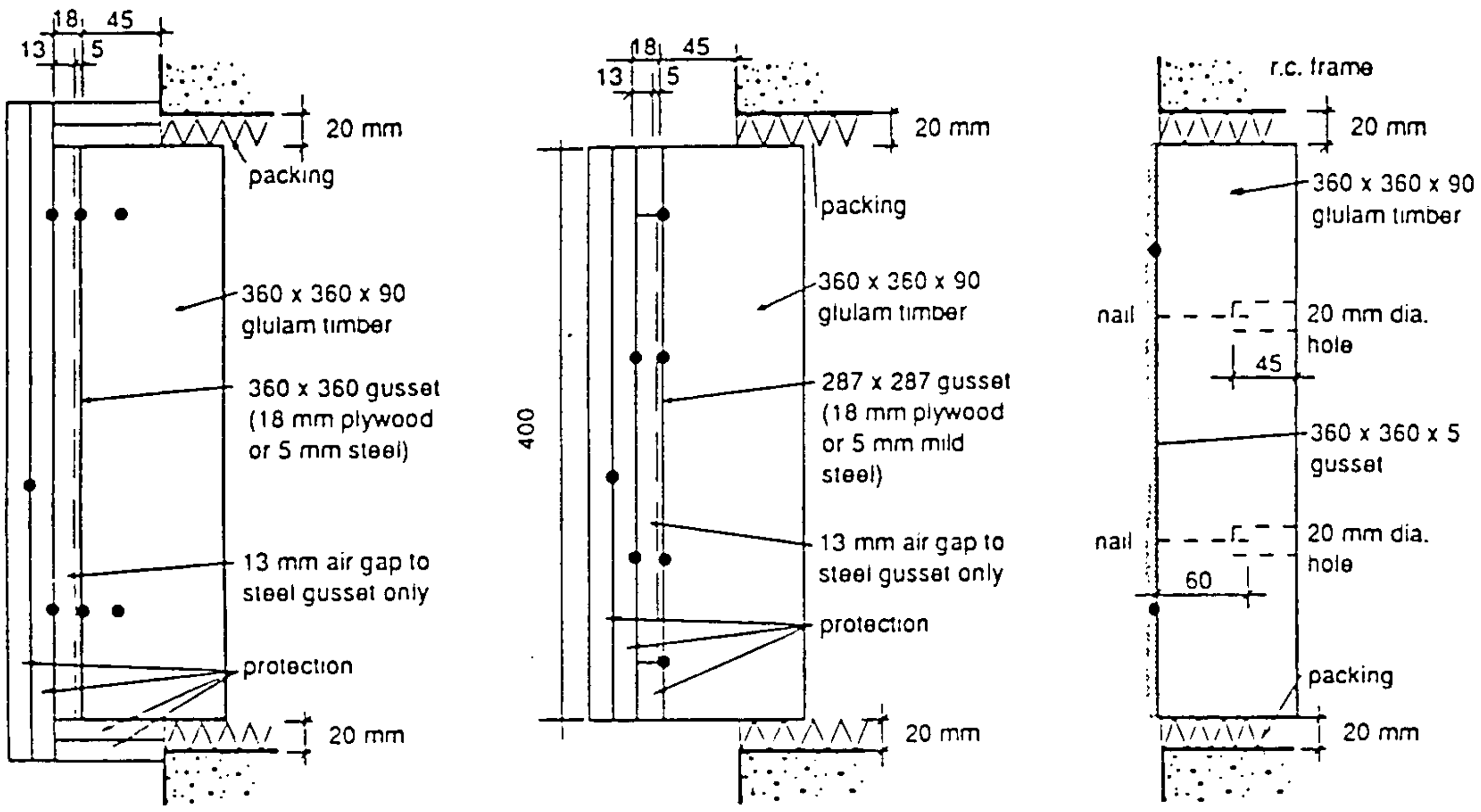
1 (d) Configuration of unprotected gussets

Notation:

- - - - Joint location

● Joint thermocouple location

Figure 1 : Block specimen details



2 (a) : Arrangement A

2 (b) : Arrangement B

2 (c) : Arrangement C

Notation:

● Joint thermocouple location

Figure 2 : Protected gusset specimens

3 RESULTS AND DISCUSSION

3.1 Block Tests

Timber is unique in that it forms an insulating charcoal layer as it burns. The thermal conductivity of charcoal is about one half to one third that of unburnt timber (Hall et al, 1980). The results of the block tests indicated that the charring characteristics of resorcinol glued timber were similar to those of solid timber (Sauvage, 1985). Their temperature development curves had the same characteristics as the timber specimen (Figure 3). There was no evidence of glue melting or delamination. The samples effectively burned as one section.

The charred zones at the mid-section of the solid and glued samples were about 38 to 40 mm deep giving a charring rate of 0.63 to 0.67 mm per minute. This compares favourably with the commonly accepted char rate of 0.6 mm per minute (SANZ 1987).

For the sliced sample with nails only, the outer laminate was completely charred and started shrinking and warping after 15 minutes. The second laminate then deteriorated in a similar fashion with a gap opening up between the laminate and the base block after 45 minutes. An interesting feature was that even when a gap (2 to 3 mm wide) was visible between the lamination and the base block, the timber temperature (which was measured 5 mm adjacent to the gap) was less than 100°C, the furnace temperature being around 900°C at that time. As the gap became wider, the outer timber lamination further disintegrated and fell off after 55 minutes. It was concluded that such nailed laminated joints should not be treated as one section when determining their fire resistance rating.

For the paper-faced gypsum plasterboard protected sample, the initial temperature rise 45 mm within the specimen, was more rapid than was the case within either the natural timber or the glulam specimen indicating that the insulation provided by the boards during this phase was less efficient. However, after 35 minutes, this situation was reversed and the specimen temperature remained low (<100°C) for the remainder of the test period. The glulam block, apart from the edges which were not protected, was uncharred at the end of the test. The exposed face of the protection developed a crazed pattern of fine cracks during the test and the outermost board lost adhesion when water was sprayed at the end of the test. The inner boards remained attached to the glulam specimen.

3.2 Unprotected Gussets

Both the plywood and the steel gusset specimens were damaged beyond repair at the completion of the test. The unprotected plywood gusset disintegrated and fell from the specimen 45 minutes into the test. Because of the good conductivity of the steel gusset, the charring characteristics of the timber beneath these gussets was similar to that of the fully exposed specimens. A gap of 10 to 15 mm between the steel gusset and the charred timber had developed by the end of the test. It was concluded that both joints were unsatisfactory without protection.

3.3 Protected Gusset Tests

Graphical Results: The temperatures at the timber face behind different types of protection are shown in Figure 4 for protection configuration A (protected on all sides) and C (intumescent coating)

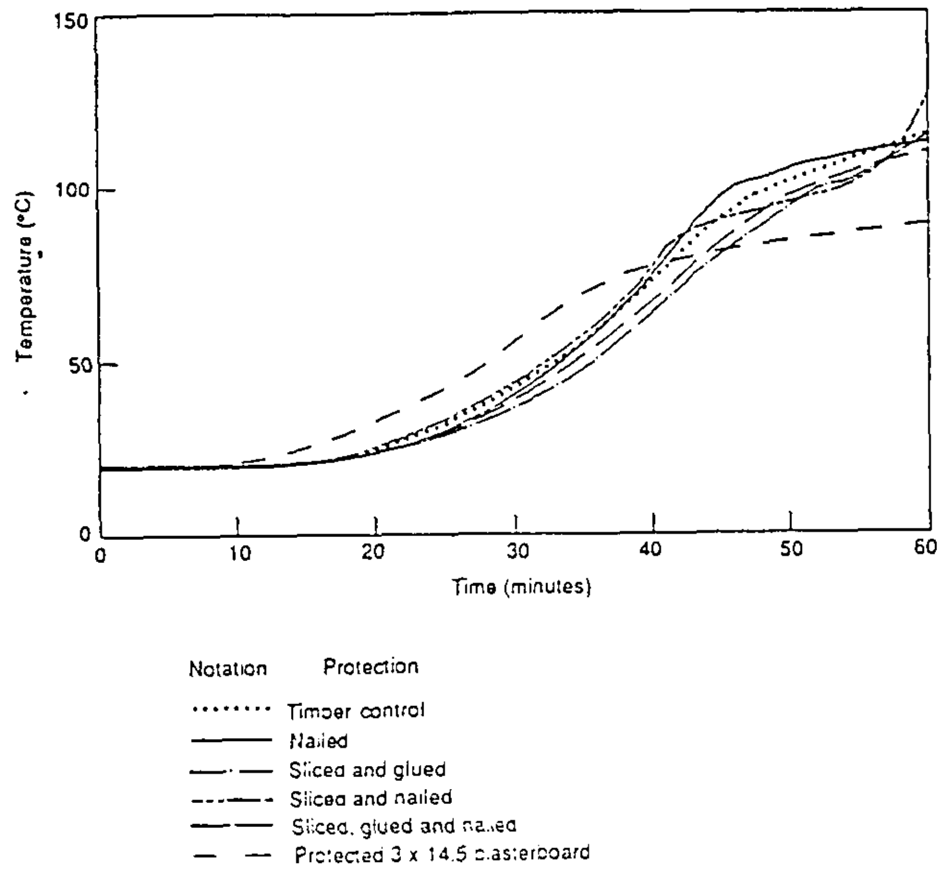


Figure 3: Block test temperatures
(at mid-depth of block)

3.3.1 Solid Timber Protection: The solid timber protections charred and shrank with a characteristic pattern of cracking in the charcoal, i.e., large chunks of charcoal separated by deep fissures. There was a tendency for the timber protection to warp, thus causing an integrity failure. The extent to which this occurred depended on the grain configuration and the presence of defects in the protective timber. It was able to be overcome by adequate adhesion and fixings. All the timber protections remained in position throughout the test. It was considered that the 40 mm thick solid timber performed well as protection for the gussets (Figure 4) and confirms the German design data for this type of protection (DIN 4102, 1981).

3.3.2 Plywood Protection: The charring characteristics of the plywood protection were markedly different to those of solid timber, i.e., there were more shallow cracks closely spaced in the veneers, which were related to the way the plywood was manufactured. The plywood deteriorated rapidly during the last 15 to 25 minutes of testing and most of it fell from the specimen, resulting in char damage to the surface of the plywood gussets and the timber underneath the steel gusset. Some delamination was also observed in the plywood protection. This result was unexpected as it had been anticipated that the plywood would behave in a similar manner to the solid timber. It was considered that the performance of two layers of 18 mm thick construction plywood as protection was inferior to other materials considered and inappropriate for a one hour protection.

In both the plywood and solid timber protected samples, there was no sign of the glue melting. The majority of the glued joints maintained their bond during the fire exposure, both in the charred and uncharred wood zones. However, separations occurred at some locations where the timber shrinkage was significant, or at joints where the shrinkage characteristics between components in different directions were incompatible, e.g., between surface and side protections.

3.3.3 Plasterboard Protection: The paper-faced gypsum plasterboard protection exhibited surface crazing and some minor crumbling at the conclusion of the test (i.e., the 19 mm thick boards and the exposed layer of the 14.5 mm thick boards). The inner of the two 14.5 mm boards, although suffering from minor damage, was still sound. However, the board-to-board joints had opened with the adjacent surfaces showing signs of crazing. The board-to-timber joints performed well with a bond maintained till the end of the test for both board thicknesses.

These results indicate that the resistance of the protection to the penetration of heat is largely determined by the thickness of the gypsum board protection. The two layers of 14.5 mm thick boards performed well as protection, without any damage to the gusset or the timber. However, the rate of temperature rise at the specimen surface beneath the 19 mm thick board increased after about 37 minutes of fire (Figure 4), with an average charred depth of 7 mm resulting over the plywood gusset at the end of the test.

The onset of surface charring beneath the 19 mm board is considered as "failure" of the protection under the test failure criteria (refer 3.7 below). However, the application of such failure criteria to these joints is open to debate and the

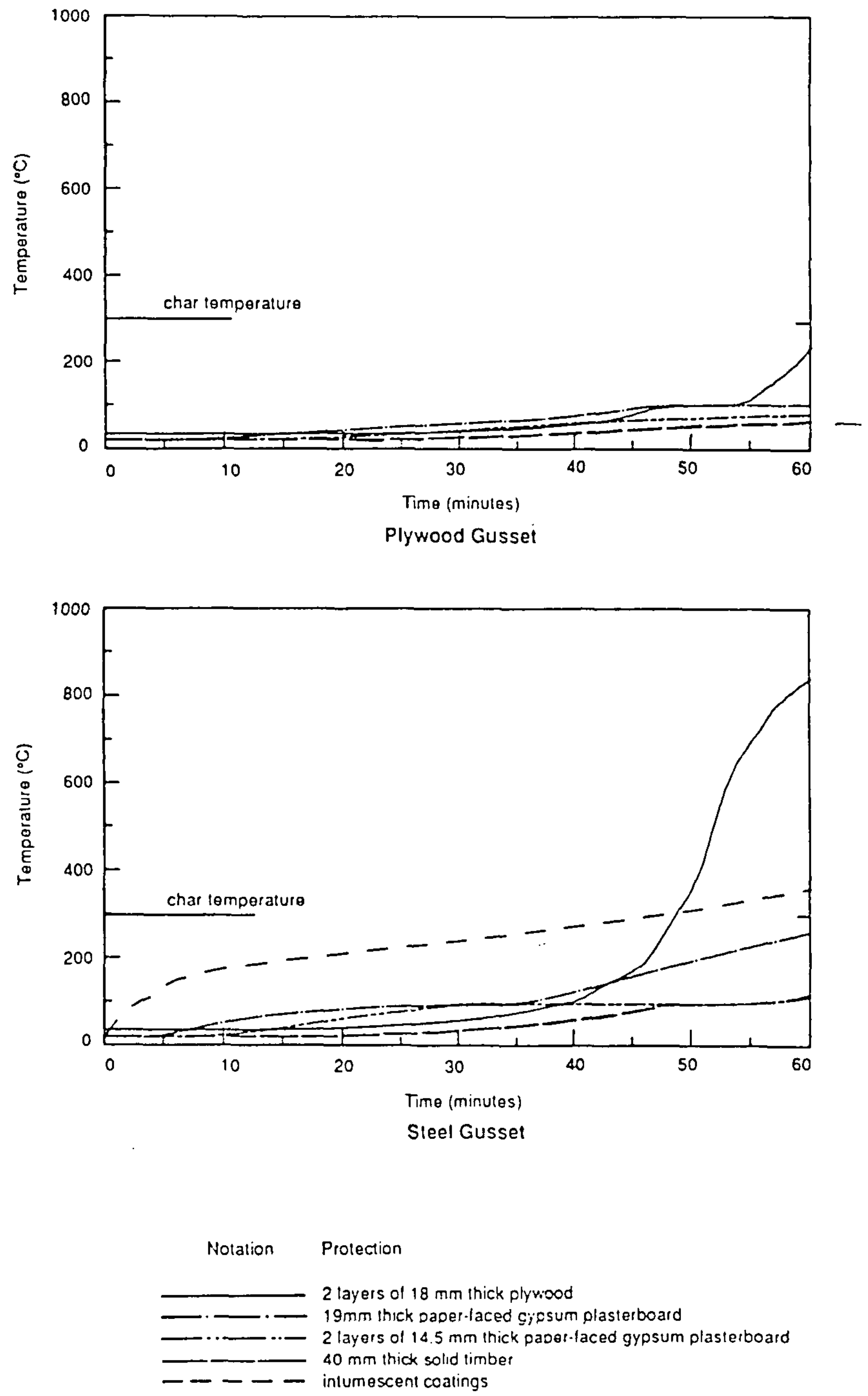


Figure 4 : Glulam timber surface temperatures, arrangement A

significance of this charring on the ability of the joint to transmit load needs to be assessed. Charring did not occur beneath the two layers of 14.5 mm thick boards which was deemed to be satisfactory.

3.3.4 Intumescent Coating: For specimens protected by the intumescent coating, the intumescent reaction began at 2.25 minutes. At first the reaction was relatively violent, then gradually developing into a steady state of coating expansion, changing the surface colour from white to black and eventually yellow. The final thickness of the coating was about 65 to 75 mm. When water was sprayed at the end of the test, the coating lost adhesion.

The time-temperature characteristics are shown in Figure 4. The initial rapid increase in steel temperature was because the coatings only began to react at temperatures of around 150 to 250°C. Thereafter, the insulation effect was secured until the end of the test with the steel temperature rising at a steady rate.

Generally, this type of protection for steel loses favour when the section factor (ratio of perimeter exposed to fire to the cross-sectional area) of the member becomes too high for the coating to provide adequate protection i.e., the higher this ratio the more heat will be absorbed. In this case, the factor is 206 m^{-1} and the steel plate heated up quickly to 200-250°C, at which temperatures strength and rigidity reduction begins to become significant (Bennetts, I.D. et. al; 1987) The timber beneath the gusset started to char after about 45 minutes (Figure 4). The depth of the charred zone at the end of the test was 3 to 5 mm.

On the whole, indications are that this system is unsuitable as an independent protection for this form of steel gusset.

3.4 Performance of Different Protection Configurations

The temperature characteristics of the timber behind the protective material was similar regardless of whether it was configured as A or B (refer Figure 4). The edge effects of each configuration was however quite different. In configuration B the sides of the glulam timber charred and shrank because they were not protected. This shrinkage resulted in some of the joints opening between the gusset side protections and the glulam opening. This became more pronounced towards the end of the test.

Configuration B had the gusset set back from the edges of the timber member with the intention of permitting the timber at the sides to be sacrificed. However, this configuration was considered unsatisfactory because:

(1) The variability of the depth of char frequently resulted in the charring extending beneath the gusset toward the nails thereby reducing their effectiveness.

(2) The charring of the timber normally extends to areas beneath the gusset, affecting the integrity of the gusset and the nails.

(3) The necessity to recess the gusset in from the edge of the timber member results in a significant reduction of the joint moment capacity, frequently in a area of maximum applied moment (as is the case at the knee of a portal).

Hence protection configuration B is not recommended unless these issues are resolved.

3.6 Plywood and Steel Gussets

The presence of the plywood gusset itself provided some insulation at the surface of the timber. The temperature development characteristics (i.e., the difference in temperature between the outer and inner faces of the plywood gusset) were similar in the protected arrangement to those observed in the unprotected case.

For the steel gussets, some insulation was provided by the enclosed air gap between the gusset and the underside of the surface protection. Hence, unlike the unprotected cases where the timber surface temperatures resembled those of the furnace atmosphere, the surface temperature of the timber beneath the steel gusset was lower than that underneath the protection.

3.7 Design and Failure Criteria

Definitive failure criteria for joints are not stated in AS 1530.4. The beam (member) itself is required to exhibit structural adequacy (maximum vertical deflection less than 1/30 of the clear span). Joint relaxation must be limited to satisfy this requirement. Full scale loaded testing would be required to demonstrate compliance. To avoid the expense of such testing, this study introduced integrity and insulation criteria for the protection with a view to being able to compare different types of protection with a "control" protection which could be achieved within the pilot furnace. The performance of the joint with "control" protection would require full scale testing under load to validate its structural adequacy. The results of such testing may require the integrity and insulation criteria below to be modified.

For this study therefore the following failure criteria were applied:

Structural Adequacy: Failure in relation to structural adequacy should be deemed to have occurred at collapse. In order to prevent collapse, the steel gusset temperature shall not exceed 550°C, and the nails will maintain their load carrying capacity.

Integrity: The protection shall resist the passage of flame into the gusset connection. Integrity failure shall be deemed to occur upon collapse of the protection, or when cracks, fissures or other openings in the protection system are of sufficient size (>3 mm) to permit flames or hot gases to penetrate to the connection.

Insulation: Insulation failure is deemed to occur when the gusset or timber temperature reaches 300°C. If the conventional criteria for steel and timber members are applied to the connections, the temperatures of protected steel and plywood gussets should be less than 550°C and 300°C respectively. For steel gussets, the temperature at the timber surface is similar to that of the steel, thus the timber charring temperature would be the controlling factor.

3.8 A Note on Protection Systems

The selection of a suitable joint protection system will depend on the fire resistance rating required, the joint geometry, the reliability, durability, compatibility, space and installation requirements, ease of replacement as well as appearance. The use of a combination of protecting materials and the standardization of protection details may provide the most efficient solution.

The importance of good detailing in protection systems cannot be overemphasised. Fire attacks thin sections and sharp corners much more readily than flat smooth surfaces. Also cracks, gaps and concealed openings encourage an increased rate of destruction.

A general objective in designing fire protection systems should be to achieve smooth, flat, unbroken surfaces and joints which are carefully detailed and fabricated to be close fitting, and will remain so during fire attack. Workmanship is of great importance. Whilst the fire behaviour of glulam frames is now accepted within New Zealand (Standards Association of New Zealand 1987), the structural performance of the members within the frame is very dependent on the behaviour of the joints between members. The behaviour of the joints is dependent on the protection itself and on the joint details of that protection. This clearly illustrates that engineering excellence requires attention to the last detail.

4 CONCLUSIONS

(1) The substantial amount of research undertaken overseas to determine appropriate means of protecting connections between timber members under standard fire conditions, is not applicable to the large steel nail-on gussets frequently used in New Zealand. Hence a specific study of these forms of connections is warranted.

(2) Unloaded gusset plate joints cam achieve a one hour fire resistant rating (FRR) when protection is provided by suitable means. The behaviour of loaded joints may differ from those tested and conclusions about their performance cannot be drawn from this series of tests.

(3) The 40 mm thick solid timber protection and the double layer of 14.5 mm paperfaced gypsum plaster board protection provided the unloaded joint with a 1 hour FRR. Both forms of protection exhibited superior insulation compared to the 19 mm thick paperfaced gypsum plaster board, the two layers of construction plywood and the intumescent coating.

(4) The effectiveness of a protection system depends on the thickness and properties of the protection materials as well as the adequacy of its attachments.

(5) The arrangement of protecting the connections on all sides is more efficient than protecting the gussets only.

(6) Glulam timber members exhibit a similar fire response to natural timber members.

(7) Glued laminated joints behave in a predictable manner without deterioration at the glue line. Nail-laminated joints degrade and open at the joint resulting in unsatisfactory fire performance.

(8) Unprotected nailed plywood and steel gusset connections cannot achieve a one hour fire resistance rating.

(9) Construction plywood burns in quite a different manner to timber or glulam and should not be substituted for solid timber in fire conditions.

REFERENCES

Aarnio, M. and Kallioniemi, P. 1983. Kantavien puurakenteiden liitoksen palonkestavyys (Brandsakerhet hos fogar i barande trakonstruktioner) (in Finnish, title translates to - Fire safety in joints of loadbearing timber structures). Technical Research Centre of Finland (VTT), Fire Technology Laboratory, Research Report No. 233. Esbo.

Ahlen, B. and Mansson, L. 1979. Experimentell undersokning ar staldetaljers inverkan pa brandmotstandet hos limtra (in Swedish, title translates to - Experimental investigation of the effect of steel details on the fire resistance of glued laminated timber). Swedish Council for Building Research, Report No. R48:1979. (Translated by McNamarra, B. and Bastings, D., Building Research Association of New Zealand, 1982).

Bennetts, I.D., Proe, D.J. and Thomas, I.R. 1987. Guidelines for Assessment of Fire Resistance of Structural Steel Members. Australian Institute of Steel Construction. Melbourne.

British Standards Institution. 1978. Structural use of timber, part 4, fire resistance of timber structures, section 4.1, method of calculating fire resistance of timber members. BS 5268, Part 4. London.

Carling, O. 1986. Brandmotstand hos infastningsdetaljer och forband i barande trakonstruktioner (in Swedish, title translates to - Fire resistance of joint details in loadbearing timber construction - a literature survey). The Royal Institute of Technology, Building and Material Science Report, TRITA-BYMA 1986:2. Stockholm. (Translated by Harris, B. and Yiu, P.K.A., Building Research Association of New Zealand, 1988).

DS 413. 1982. Dansk Ingeniorforenings norm for traekonstruktioner (in Danish, title translates to - Danish Engineering Association Standards for timber construction). Technical Publisher. Copenhagen.

German Standards Institution. 1981. DIN 4102:1981: Part 4. Fire behaviour of building materials and building components; synopsis and application of classified building materials, building components and special building components.

Hall, G.S., Saunders, R.G., Allcorn, R.T., Jackman, P.E., Hickey, M.W. and Fitt, R. 1980. Fire performance of timber - a literature survey. Timber Research and Development Association. High Wycombe, Buckinghamshire.

International Standards Organisation. 1975. Fire-resistance tests - elements of building construction. ISO 834-1975.

Jackman, P.E. 1981. The fire behaviour of timber and wood based products. Journal of the Institute of Wood Science, 9(1): 38-45.

Norwegian Standards Institute. 1981. NS 3478 Brannteknisk dimensjonering av bygningskonstruksjoner (in Norwegian, title translates to - Fire resistance design of timber structures). Oslo.

Sauvage, M.E. 1985. Determination of the behaviour of wooden building components and wood-based panels exposed to fire. Commission of the European Communities, Report EUR 9485 EN.

Standards Association of New Zealand. 1987. Fire properties of building materials and elements of structures. MP9: 1987. Wellington.

Standards Association of Australia. 1985. Fire-resistance tests of elements of construction. AS 1530. Part 4 - 1985. Sydney.

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