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The Fire Performance of Protected Nail-on Gusset Connections for Loaded Glulam Members

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THE FIRE PERFORMANCE OF PROTECTED NAIL-ON GUSSET CONNECTIONS FOR LOADED GLULAM MEMBERS

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ABSTRACT

The fire performance of heavy glulam timber members based on the 'sacrificial method of char' is widely accepted. The performance of their mechanical connectors, possibly the weakest link, is frequently overlooked. This paper describes the experimental testing of six full-size nail-on gusset connections between glulam timber members when subjected to the ISO 834 (1975) fire resistance test. The parameters examined included different gusset types, different protection methods, beams of two depths and two levels of applied load.

The results of this study indicated that protected nail-on plywood or steel gusset connections can achieve a one hour fire resistance rating (FRR). Protection using two layers of a gypsum "control board" proved to be more than adequate with a single layer achieving the one hour FRR. The degree of protection offered by an intumescent paint coating on the steel gussets was inconclusive.

INTRODUCTION

In New Zealand, glulam timber portal frames are found in educational, industrial, recreational, commercial and agricultural buildings. The fire resistance of such structures is provided by using 'heavy' members and based on the 'sacrificial method of char'. On the other hand, the mechanical connection between such members, possibly the weakest point, is frequently overlooked.

Hvild (1980) pointed out that such joints may become the weak link of structures, partly due to the reduced strength of the steel gusset at elevated temperatures, and partly to the weakening and increased charring of the wood in the embedding zones caused by the heat conducted by the fasteners. Odeen (1985) claimed that the high thermal conductivity of steel plates leads to a local increase of charring rate and consequently to a rapid breakdown of the joint and the structure.

The Building Research Association of New Zealand (BRANZ) undertook a research programme to determine whether a one hour FRR to nail-on steel or plywood gussets is practical to achieve. The first phase of the programme tested various methods of protection on unloaded nail-on plywood or steel gusseted glulam blocks subjected to the one hour ISO 834 test in a pilot furnace (Yiu and King 1989). The study concluded that 40 mm solid timber or two layers of 14.5 mm thick paper-faced gypsum plasterboard were likely to achieve a one hour FRR on plywood and steel gussets.

The second phase of the programme comprised subjecting six loaded, protected nail-on gusset connections to the ISO 834 (1975) time temperature conditions. Protection was provided to the gusset joints by using a gypsum-based board identified throughout this paper as "control board". One specimen was tested with an intumescent paint coating applied to steel gussets.

EXPERIMENTAL DESIGN

Five of the specimens tested were of 540 x 135 mm cross-sections and the other 630 x 135 mm The test arrangement is shown in Figure 1 The experiment simulated the loaded condition at a knee joint of a portal frame. The test joints were fabricated at the butt joint between sections of straight glulam beams Fire protection was provided to the joint as shown in Figure 2. The glulam beams were fabricated from untreated Pinus radiata (sourced from Nelson Plantations) of No.1 Framing Grade using 45 mm laminations. They were conditioned to 12% moisture content and had an average density of 460 kg/m^3 The members were subjected to uniform bending moment over the 4.5 m furnace span by suspending load masses (concrete blocks) beyond the furnace Lateral restraints were provided at one third span using timber blocks as shown in Figure 1 The beams of Test 2 were fabricated from those in Test 1 by cutting off the sections exposed to the furnace and joining the remaining sections. The specimens were preloaded for one hour before each test

The test beams were sized within the mid-range of portal frames typically used in New Zealand. Since this work was concerned with the joints, the applied load comparable to the joint load in a fire condition was considered. The characteristic (5 percentile) capacity nail load has been taken as 2.4 times the basic nail load given in NZS 3603, Standards Association of New Zealand (SANZ) 1981. Assuming that dead load = live load for a typical design situation, then the nail load under fire attack was determined at half capacity of the cold joint, i.e 1.2 times the basic nail load as specified in NZS 3603 (SANZ 1981). To study the effects of different load levels, the nails in beam X1 were stressed to 1.8 times the basic load. Figure 3a shows the nailing pattern of the 30 mm plywood gussets while Figure 3b shows the nailing pattern of the 5 mm steel gussets. The MP9 (SANZ 1987) recommendations, using a char rate of 0.6 mm/min for 60 minutes on all four faces of the 540 mm deep section and applying a factor of 2, leads to an applied load of 45 kN-m The capacity of the residual section, when lateral buckling was considered, was 35 kN-m

The results of Test 1 using two layers of "control board" indicated that this degree of protection was unduly conservative and the protection was subsequently reduced to one layer of this board for Test 2. The specimen details are as shown in Table 1

RESULTS

Test 1

Beam X2 failed after 50 minutes and the test was stopped. After removal from the furnace seven minutes later, a fracture was observed about midway between one support and the protected joint The fracture did not appear to have involved the uppermost (tension) laminations. All the exposed beams were heavily charred away from the protected joints but the plywood gussets were not charred. There was no visible nail slip in the joints. The lateral bracing elements were also heavily charred.

Test 2

Beam W2 failed at 53 minutes and the suspended weights on this beam were removed. The test continued for the 60 minute target time without other failures. After removal from the furnace four minutes later, beam W2 had a fracture about 1 m from the same support as for the fracture of X2. Contact regions between the beams and the lateral bracing elements had been protected by a 19 mm gypsum plasterboard. These did not char and thus remained effective throughout the test.

Joint W2: A 20 mm clear gap developed between the gusset and the char face around the perimeter of the steel gusset where the timber had charred. Charring to a depth of 60 mm was observed along the top and bottom of the beam within the joint area. The outer two rows of nails, which were partially exposed due to this charring, had deformed and were no longer able to carry load. The steel gussets themselves were also distorted and warped. When a corner of the gusset was removed, an average char of 20 mm was observed beneath the plate.

Joint X3: The single layer of "control board" was still attached at the completion of the test. The plywood gussets were charred to a depth of 15 mm on the inner face (the face towards the centre of the furnace) and 10 mm on the outer face. The outer layers of the plywood gussets had delaminated and surface cracks had developed. Charring also occurred along the top and bottom faces of the beam, being more severe along the bottom face. The nails could easily be dislodged by hand from the beam and gussets where charring had occurred. Nail slips up to 1 mm were also apparent in the plywood gussets.

Joint W1: The steel gussets were not damaged and the charring of the joint was predominantly on the top and bottom faces of the beam. When corners of the gussets were removed, 6 mm of char was observed on the inner and 1 mm on the outer face. Nail slips up to 1 mm were also observed in the timber beneath the gussets.

For the two outer beams (W1 and X3), measurements indicated that in each case the inner face of the beam (the face towards the centre of the furnace) had an average char depth 10 mm greater than that measured on the outer faces in the area outside the gusset protection. This was consistent along the length and across the depth of the beam. Although there were variations in the depth of char across the depth of the beam, there was no apparent correlation between char depth and the position of gluelines.

DISCUSSIONS

Different Protection Methods

The joints protected by two layers of "control board" remained fully functional. The surfaces of the gusset were not charred during the 50 minutes of standard test and the subsequent seven minutes of lesser heating when the specimens were removed from the furnace, before being extinguished with water. The joints protected by one layer of "control board" continued to carry their imposed load for the one hour of standard fire test exposure and were considered to achieve a one hour FRR.

Though the failure of beam W2 was remote from the joint after 53 minutes, the condition of the joint observed following the completion of the test (60 minutes) was such that its ability to carry the load up to one hour is considered doubtful. As shown in Figure 4a, the glulam beneath the gussets commenced charring after 15 minutes of the test (assuming an 'onset of char' temperature of 300 degrees C). Furthermore, at the time of failure, the deflection of the joint was 139 mm (compared with 64 mm for joint W1) and was increasing rapidly towards the failure criterion of 1/30 of span (150 mm) outlined in AS1530, Part 4, Standards Association of Australia (SAA) 1985. The 35 mm edge distance allowance for charring (above and below the gussets) was insufficient to prevent the nails from being exposed to furnace conditions with charring penetrating to the second row of nails.

Plywood (X3) and Steel (W1) Gussets

Both beams exhibited similar deformation characteristics up to about 57 minutes as shown in Figure 5a. At one hour, the vertical joint displacement of X3 was 47 mm compared to 64 mm for W1. The plot of joint rotations against time (Figure 5b) indicated that, up to one hour, the joint with the steel gussets had smaller rotations and was therefore slightly more rigid.

Position within Furnace and Failure Mechanisms

In both tests, failure occurred within the central member away from the protected joint and towards the same end of the furnace. In Test 1, the central beam was at a lower level of stress than one outer beam which did not fail.

Hall (1968) tested four glulam beams using a furnace of the same width (3.05 m) but of a shorter length (3.6 m) and concluded that the two outer beams were more resistant and attributes this to slightly different heating conditions. Hall's test subjected the beams to a uniform loading regime, with full support of the compression flange through contact with the loading surface. The predicted failure time was 43 minutes assuming a charring rate of 0.64 mm/min and actual failure of the first beam (central) occurred at 53 minutes, and the test was stopped. The average furnace temperature below the central beams measured in both Test 1 and Test 2 of this BRANZ series was slightly higher than that beneath the two outer beams.

It is postulated that when the outer beams in the BRANZ tests began charring, they acted as a source of radiation for the central beam (and vice versa) thereby consequently increasing the charring of the central beams and of the inner faces of the outer beams. This is consistent with the char depth being an average of 10 mm greater on the inner faces than on the outer faces of the outer beams. Furthermore, the temperature rise of thermocouples within beam W1 (embedded 45 mm into the beam, facing towards the centre of the furnace) was more rapid than those of beam X3 (facing away from the centre of the furnace, Figure 1b). A further possible explanation is that the outer surfaces of the outer beams received heat from the furnace gases but lost heat to the relatively cooler concrete walls of the chamber.

Failure of the central beams was thought to have been caused by lateral instability of the residual section of each beam, which may have initiated fracture at the compression flange. Lateral restraint mechanisms were provided to this flange in both tests. In Test 1, as the beams deformed upwards, the soffit of the beam charred, as did the faces of the restraint blocks. Thus the restraint became ineffective. In Test 2, the inner faces of the restraining blocks were protected with 19 mm gypsum plasterboard and continued to restrain throughout the test. However, the reduction in section width was greater than calculated, and could have resulted in lateral buckling occurring between the beam support and the restraint point.

Variations in Member Sizes (X4 and X2)

The joint displacement of the 630 x 135 beam was smaller than for the 530 x 135 beam indicating that the bigger member performed better. The joint displacement of the smaller section increased markedly after about 35 minutes (Figure 5c).

Whilst the beam stiffness is enhanced with increases in section depth, it is the width of the section which dictates the lateral buckling resistance of the member, particularly in a fire environment. Timber purlins, claddings and some other bracing members may well become ineffective as restraints against lateral buckling when subjected to fire attack. Particular attention should also be given to the connection of bracing members. Bracing utilising steel members would likewise become less effective with increasing temperature.

Different Load Levels (X1 and X2)

Both beams deformed steadily up to about 30 minutes but the lightly stressed central beam (X2) deformed more rapidly after about 35 minutes resulting in its displacement being greater than that of the higher stressed beam (Figure 5c) at the completion of the test. The beam surface temperature beneath the gusset was higher for beam X2 (Figure 4b). This was not expected and is thought to be attributable to the more severe fire attack on this central beam as a result of its position within the furnace (refer above).

Previous work by Malhotra and Rogowski (1967) on glulam columns concluded that for the columns they investigated, the fire resistance was proportional to the inverse square of the load. Rogowski (1967) from the same work concluded that there is no clear indication that load affects the charring rate at an 80% confidence level. Nevertheless, with only one beam stressed at the higher level, the effects of different load levels is inconclusive.

FUTURE WORK

Charring Rate of Glulam

These tests indicated that the charring rate of the exposed sections of beams was higher than the expected average value of 0.6 mm/min given in MP9 (SANZ 1987). Further tests are needed to establish the char rate for New Zealand Pinus Radiata glulam. Tenning's (1985) work and that of others overseas has been based on unloaded beam section. Bastings (1985) quoted that for Pinus Radiata, 0.6 mm/min is adequate up to one hour beyond which cracks and splitting encouraged an apparent faster average rate.

The test setup, method of evaluation of char rate, and whether the timber is treated, may influence the measured charring rate. The parameters to be studied should include cross-sectional size, density, moisture content, load levels and exposure temperature and time. The test programme should preferably also include the monitoring of the deflection and lateral stability.

Development of a Comparative Test Method

This series of tests indicated that joints protected with one layer of the "control board" were able to carry load for the 60 minute duration of the test without excessive relaxation or failure of the joint. The behaviour of the joint is determined from the time temperature characteristics it experiences beneath the protection. These characteristics are available for "control board" protected joints, and may be used as the basis of comparison with the behaviour of proprietary products aiming to achieve this degree of joint protection.

As full scale loaded joint tests are expensive, it is proposed that a method of test be developed using specimens suitable for use within a pilot furnace. The test would yield the time temperature characteristics experienced by a specimen protected by the proprietary system, which can then be calibrated to the performance of the "control board" in the same test.

CONCLUSIONS

The following conclusions can be made:

1. Nail-on gusset connections can achieve a one hour FRR when totally protected with a single layer of "control board". The results apply to boards with no joints.

2. There was no significant difference in the load carrying behaviour between the steel and plywood gusset plates when protected by a single layer of "control board" for the one hour of exposure to the standard fire test.

3. The specimen location within the test furnace affects the performance of the member/joint.

4. There was no significant difference in performance for the two beam depths. Care must be taken however to prevent failure by lateral buckling when using deeper or narrower sections which would lead to more slender residual sections.

5. The expected average charring rate of the exposed glulam (0.6 mm/min) timber beams was significantly exceeded and requires further study.

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Notes for Table 1

(a) All beams 135 mm wide.

(b) The 30 mm plywood gussets comprised a layer of each of 12.5 and 17.5 mm Redpine Construction plywood complying with NZS 3614 (SANZ 1971) with a moisture content of 11 %.

(c) The proprietary intumescent paint coating was applied as the maximum recommended by the manufacturer.

Beam ID	Beam Depth (mm)	Type of protection	Gusset Material	Nail Load (x Basic)	Applied Moment (kN-m)	Timber Stress (Mpa)
X1	540	2 layers Control Board (CB)	30 mm Plywood	1.8	26	11.3
X2	540	2 layers CB	30 mm Plywood	1.2	17	7.4
X4	630	2 layers CB	30 mm Plywood	1.2	20	6.1
X3	540	1 layer CB	30 mm Plywood	1.2	17	7.4
W1	540	1 layer CB	5 mm Mild Steel	1.2	15	6.5
W2	540	intumescent coating	5 mm Mild Steel	1.2	15	6.5

Table 1 : Specimen Details

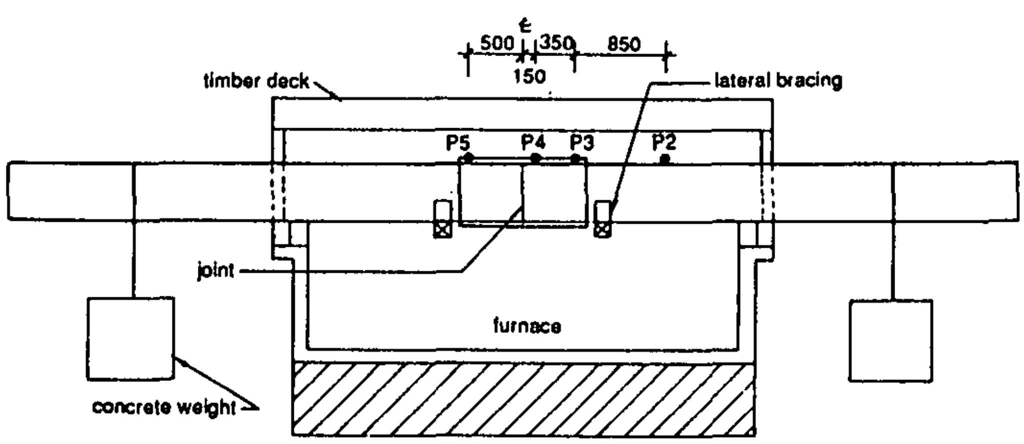

Figure 1a : Longitudinal section and deflection reading location
Pn denotes a vertical deflects measurement print

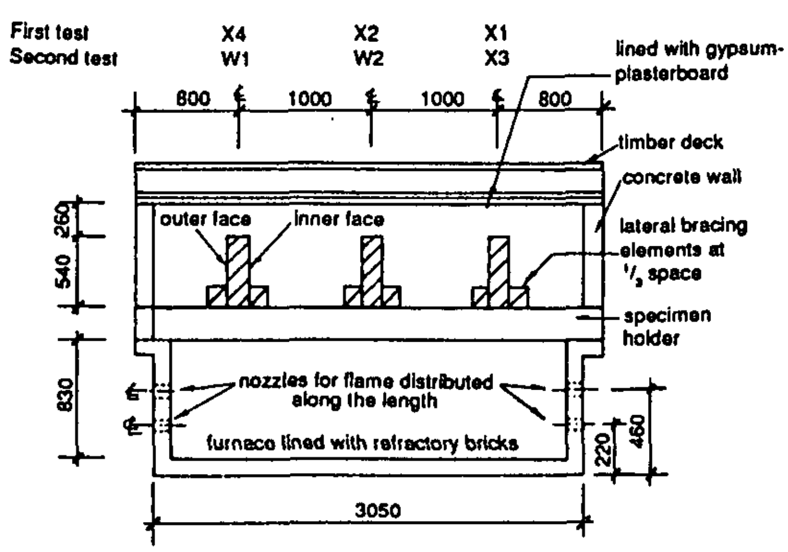

Figure 1b : Cross section

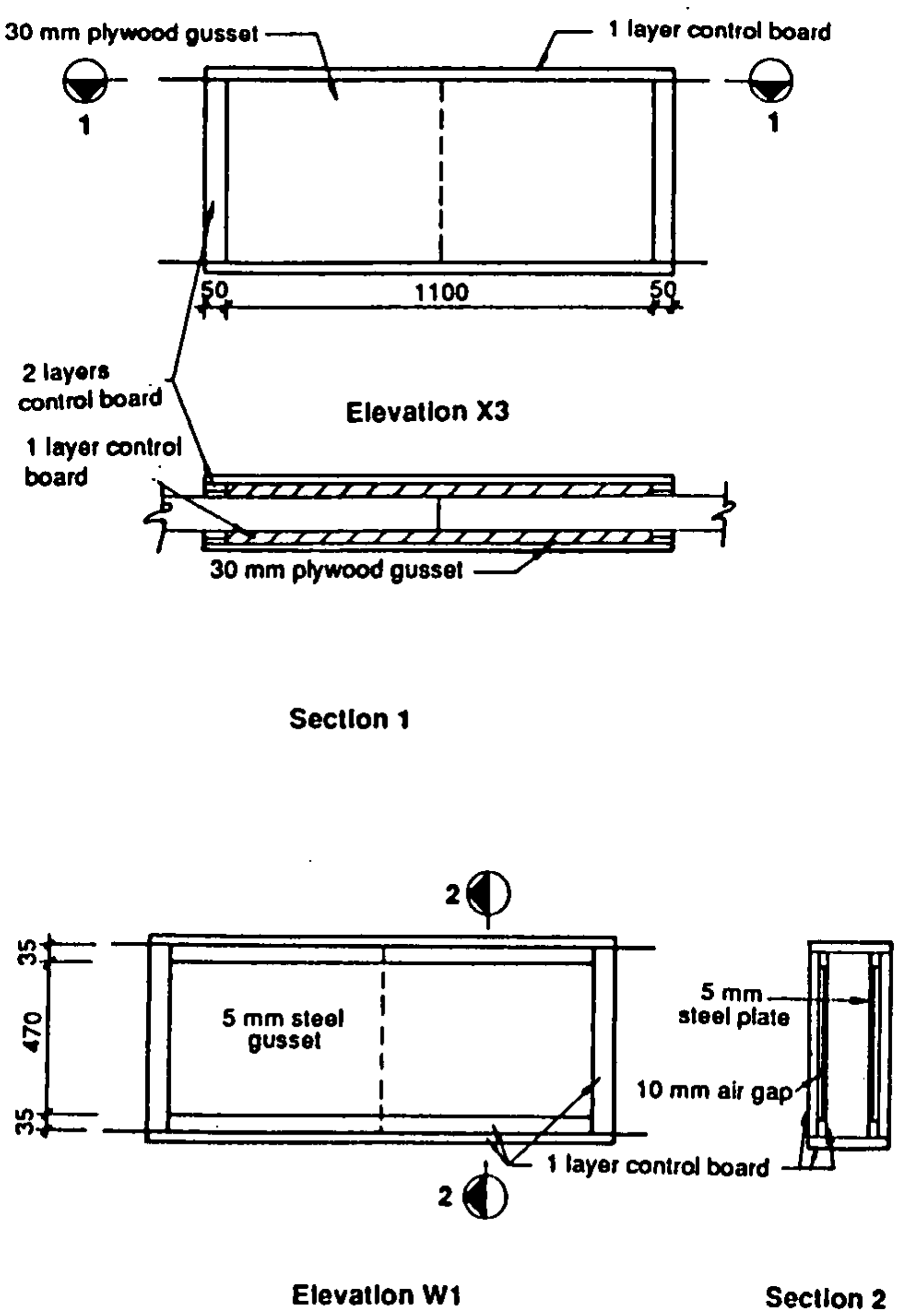

Figure 2 - Protection Details
Protection glued with 'gib-core', 'gib- fix' or screwed at 150 crs around the perimeter to the beam/gusset

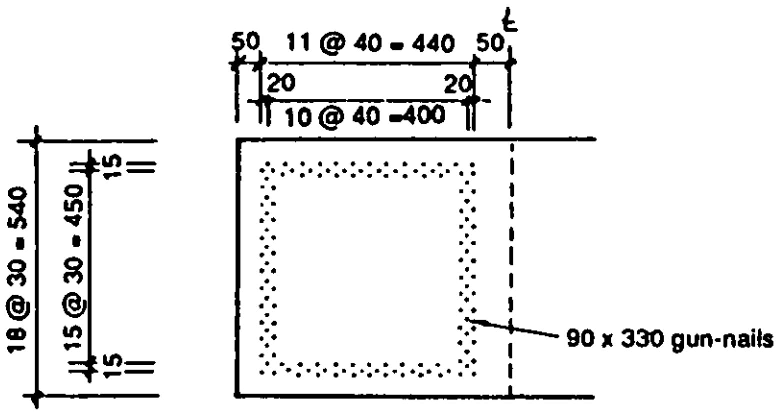

Figure 3a : 1100 x 540 x 30 plywood gusset

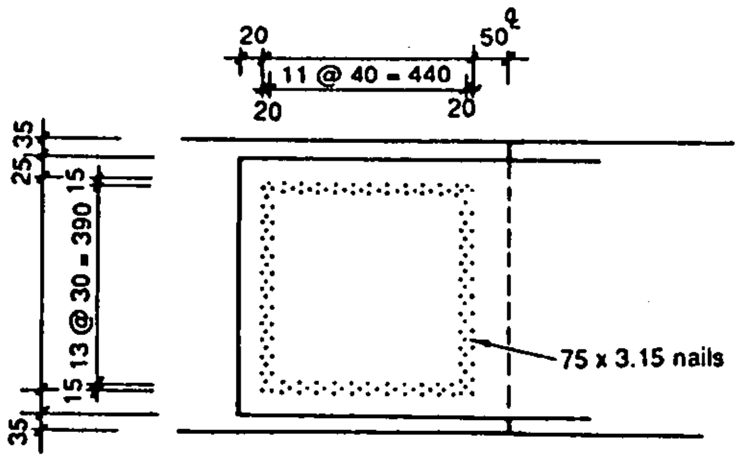

Figure 3b : 1100 x 470 x 5 steel gusset

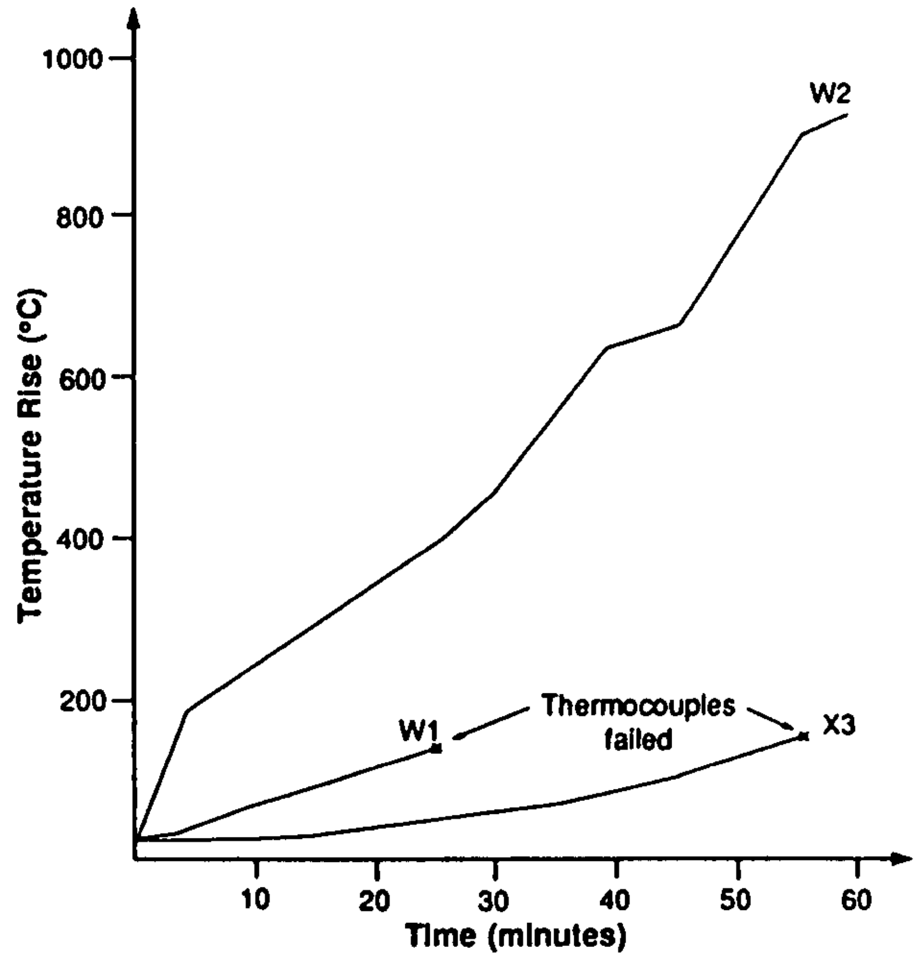

Figure 4a: Temperature on beam surface beneath gussets -Test 2

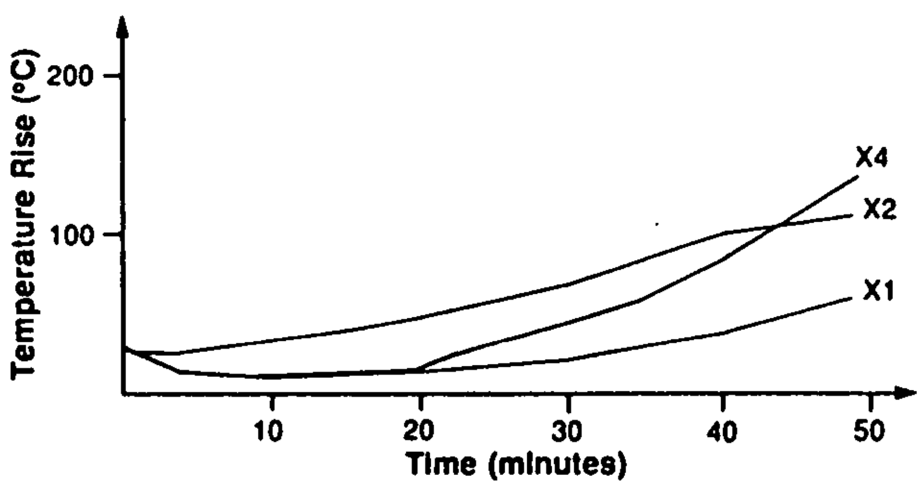

Figure 4b: Temperature on beam surface beneath gussets -Test 1.

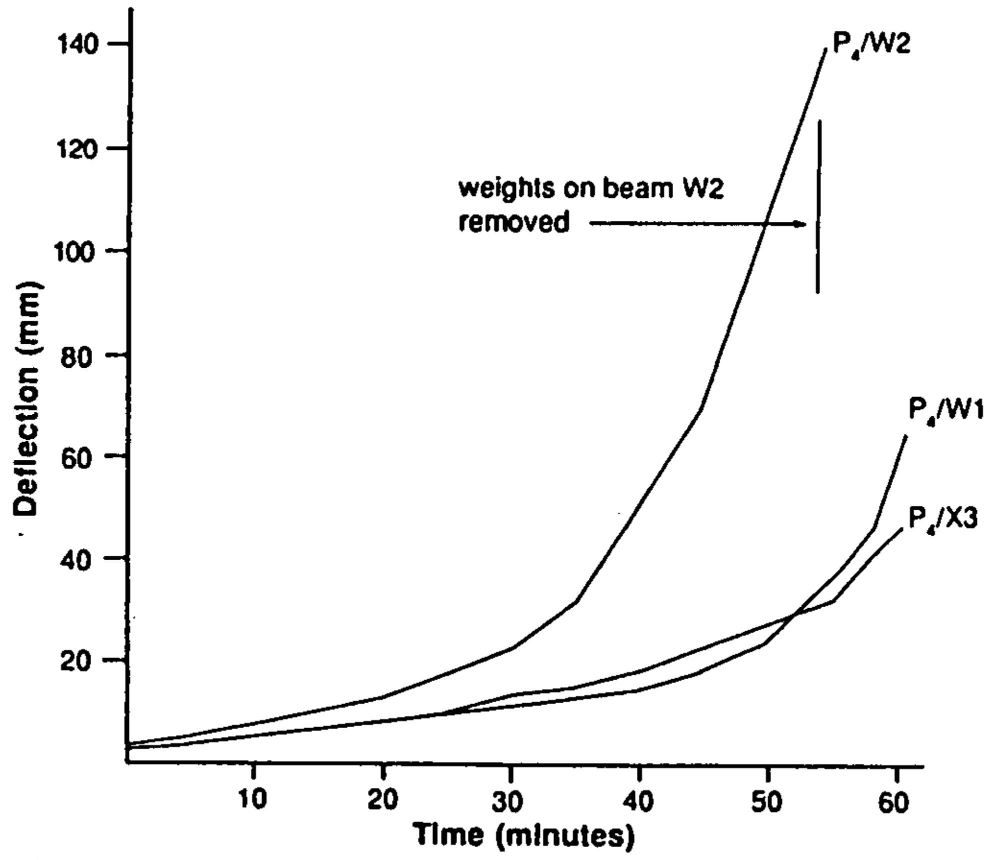

Figure 5a: Midspan deflections - Test 2.

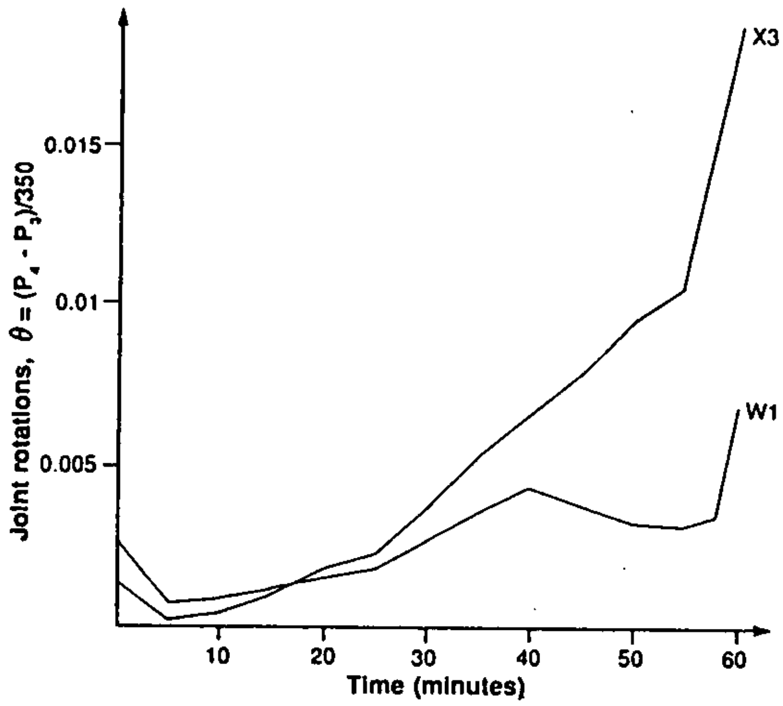

Figure 5b: Joint rotations of W1 and X3

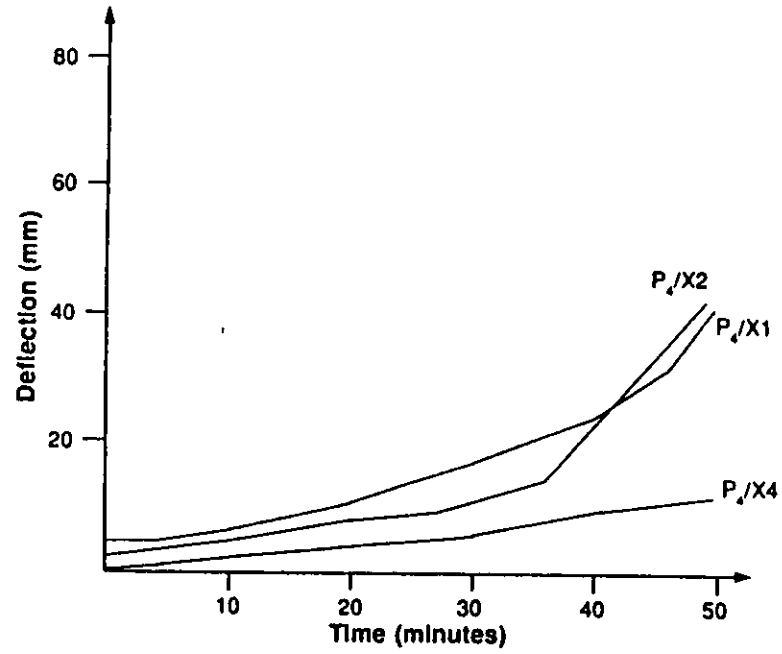

Figure 5c: Deflection at joint - Test 1.

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