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PROTECTED NAILED GUSSET CONNECTIONS FOR GLULAM MEMBERS

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PREFACE

This study forms the second and final part of a research programme undertaken by BRANZ to prepare design information for the fire performance of nailed gusset connections for fire-rated glulam members. A paper relating to this study was presented at the Pacific Timber Engineering Conference (Lim and King, 1989).

The first part of this programme resulted in the BRANZ Study Report SR 21 entitled "The fire performance of unloaded nailed gusset connections for fire-rated timber members". In conjuction with this study, a translation was carried out on Carling's work resulting in the BRANZ Study Report SR 18 "Fire resistance of joint details in loadbearing timber construction - a literature survey". Moreover, BRANZ also funded a study at Canterbury University carried out by Chinniah (1989) resulting in the report entitled "The fire performance of moment-resisting nailed connections between heavy glulam timber members".

A Technical Recommendation will be prepared for designers, as well as documenting a comparative test method for manufacturers to test their products for a 60 min FRR for nailed gusset connections.

ACKNOWLEDGEMENTS

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This report is intended for fire and structural engineers, architects, designers and other workers in the field of fire engineering research.

PROTECTED NAILED GUSSET CONNECTIONS FOR GLULAM MEMBERS

Study Report SR 29

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REFERENCE

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KEYWORDS

From Construction Industry Thesaurus - Branz edition: Bibliographies; Deflections; Failure; Fire; Fire Resistance; Full-size test; Glulam; Gusset Plates; Gypsum Plasterboard; Intumescent; Joints; Loads; Loaded; Nailed Connections; Method of Test; Plywood; Portal Frames; Protection Materials; Steel; Structural Design; Temperature; Timber.

ABSTRACT

The fire performance of heavy glued laminated (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 report describes the experimental testing of six full-size nailed moment-resisting gusset connections between glulam timber members when subjected to the 60 minutes (min) standard time temperature conditions. The parameters examined included different gusset types; different protection methods; beams of two depths, and two levels of applied load.

The results of these tests indicated that protected nailed plywood or steel gusset connections can achieve a 60 min Fire Resistance Rating (FRR). Protection using two layers of a gypsum based 'control' board proved to be more than adequate, with a single layer achieving the 60 min FRR. The degree of protection offered by an intumescent coating on the steel gussets was inconclusive.

This report also describes the experimental testing of four unloaded gusseted glulam specimens protected with a single layer of the 'control' board subjected to the 60 min standard time temperature conditions. These tests were carried out in a pilot furnace to determine the time temperature characteristics of the components beneath the protection, to enable a comparative test method to be developed.

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1.0 INTRODUCTION

In New Zealand, glulam timber portal frames are found in educational, industrial, recreational, commercial and agricultural buildings (Timber Industry Federation (TIF), 1989). The fire resistance of such structures is provided by using 'heavy' members (considered for this study to be those whose dimensions are not less than 75 mm) and based on the 'sacrificial method of char' (Standards Association of New Zealand, (SANZ) 1987). On the other hand, the mechanical connection between such members, possibly the weakest point, (Ahlen and Mansson, 1979; Smith, 1984; Carling and Odeen, 1988) is frequently overlooked.

Such connections with bolts, screws or nails provide a heat path into the interior of the timber member, which may initiate local charring with subsequent loss of anchorage or rigidity. Connections using steel plates may become the weak link of structures, partly due to the reduced strength of the gusset at elevated temperatures, and partly to the weakening and increased local charring which occurs at steel timber interfaces (Hviid, 1980; Odeen, 1985). Timber or plywood gusset plates are combustible materials which may suffer reduced strength and stiffness characteristics when exposed to fire, which may result in failure.

In New Zealand, moment-resisting connections of knee and apex joints in portal frames are often made with large steel or plywood gusset plates nailed to the wide faces of the glulam members. They possess significant ductility and hence energy dissipating capacities, enabling them to be used to resist seismic loads. The current work therefore concentrates on the fire performance of these connections.

Various researchers have tested nailed connections with plywood or steel gussets when loaded in a fire environment and concluded that such connections need to be protected to achieve a 60 min FRR (Hviid and Olesen, 1977; Kordina and Meyer-Ottens, 1977; Leicester et al, 1979). Gibson (1983) calculated that unprotected steel nailed gussets would have a FRR of about 12 minutes.

The Building Research Association of New Zealand (BRANZ) undertook a research programme to determine whether nailed steel or plywood gussets would achieve a 60 min FRR. The first phase of the programme tested various protections on unloaded plywood or steel gusseted glulam blocks subjected to the International Standards Organisation (ISO) 834 (1975) test in a pilot furnace (Yiu and King, 1989). These tests subjected only one face of the specimens to the furnace conditions. The study concluded that of the five protection methods tested, 40 mm solid timber or two layers of 14.5 mm thick paper-faced gypsum plasterboard protection were most likely to achieve a 60 min FRR with either plywood or steel gussets.

This conclusion was based on the criterion that the glulam temperature beneath the steel gusset and the plywood temperature beneath the protection should be less than 300 degrees C, the assumed temperature when charring commences. In conjunction with their study, a translation of Carling's (1989) work on the "Fire resistance of joint details in loadbearing timber construction - a literature survey" was carried out.
BRANZ also funded a study carried out at the University of Canterbury by Chinniah (1989), resulting in the report "The fire performance of nailed

gusset connections between heavy glulam members". Chinniah used Yiu and King's (1989) time temperature relationships to study the load-slip behaviour of small scale nailed plywood and steel gussets loaded in direct shear when subjected to a similar time temperature history. The report concluded that nailed gusseted connections between glulam members have good fire performance when protected with gypsum plasterboard. The nail slip observed was small, and consequential joint relaxation minimal, particularly when compared with the changes to member section properties away from the protected zone as charring developed.

Because Yiu and King's tests were unloaded, their results may not be applicable to loaded joints, hence the current phase of the programme.

2.0 FULL-SIZE TESTS

The current, and final phase, of this research programme comprised subjecting six loaded, protected nailed gusset connections to the 60 min standard time temperature conditions. Protection was provided to the gusset connection by using 14.5 mm thick paper-faced gypsum plasterboard identified throughout this report as 'control' board. Of the two protection methods identified by Yiu and King above, only the 14.5 mm thick paper-faced gypsum plasterboard was tested because the time temperature characteristics beneath the protections were similar. One specimen was also tested with an intumescent coating applied to steel gussets.

The main objective of this experimental study was to confirm that loaded, protected nailed gusseted connections can achieve a 60 min FRR. Other objectives were to assess the performance of plywood and steel gussets, different protection methods, beams of two depths, and two levels of applied load.

2.1 The Experimental Programme

2.1.1 Test Setup, Method and Instrumentation

Two full-size tests (FS1 and FS2) were conducted using the main furnace at the BRANZ Fire Laboratory at Judgeford. The furnace is diesel-fired and is lined with light-weight refractory bricks. It has clear dimensions of 4.0 x 3.0 m and was in a horizontal position. Three full-size beams were tested each time. A timber framed deck lined with gypsum plasterboard was used to close the top of the furnace while concrete walls 800 mm high and 125 mm thick closed the sides of the furnace. The temperature conditions in the furnace were controlled as specified in ISO 834 (1975). The test arrangement is shown in Figures 1 and 2.

Five of the specimens tested were 540x135 mm cross-section and the other was 630x135 mm. The experiment simulated the loaded condition at a knee joint of a portal frame. Prime (1980) claims that in such a joint, shear and axial load effects contribute only a small percentage of the nail forces that result from bending moments. The test joints were therefore fabricated at the butt joint between sections of straight glulam beams and loaded in bending only. Fire protection was provided to the joint as shown in Figure 3. The glulam beams were fabricated from untreated Pinus radiata of No. 1 Framing Grade using 45 mm laminations with an average density of 460 kg/m^3 ovendry. They were conditioned and their moisture content was measured to be 12 % at ambient temperature, using a Techtron DCR2 electrical resistance moisture meter. The members were subjected to uniform bending moment over the 4.5 m beam span by suspending load masses (concrete blocks) beyond the furnace. Lateral restraints were provided at one third of span using timber blocks as shown in Figure 1. The beams of test FS2 were fabricated from those in test FS1 by cutting off the sections exposed to the furnace and joining the remaining sections. All the beams were preloaded for one-hour before each test.

The results of test FS1 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 FS2.

Test FS1: Beams PG1, PG2 and PG4 (Plywood Gussets) fabricated with a 20 mm gap at the joint and were protected with two layers of the 'control' board. Beam PG2 was at the centre of the furnace with beams PG1 and PG4 offset 1 m each side.

Test FS2: Beams SG1, SG2 (Steel Gussets) and PG3 were fabricated with no gap at the butt joint. Beams SG1 and PG3 were protected with one layer of the 'control' board and beam SG2 (located at the centre of the furnace) protected with an intumescent coating.

The tests were planned to run for 60 minutes, or until joint failure or, a deflection of 1/30 span (150 mm) occurred. The specimen details are as shown in Table 1. The calculations of the member sizes, applied loads, joint loads and gussets are presented in Appendix A.

Beam ID	Type of protection	Gusset Material	Beam Depth (mm)	Nail Load (x Basic)	Applied Moment (kN-m)	Member Stress (MPa)
PG1	2 layers 'Control' Board (CB)	30 mm plywood	540	1.8	26	11.3
PG2	2 layers CB	30 mm plywood	540	1.2	17	7.4
PG4	2 layers CB	30 mm plywood	630	1.2	20	6.1
PG3	1 layer CB	30 mm plywood	540	1.2	17	7.4
SG1	1 layer CB	5 mm steel	540	1.2	15	6.5
SG2	intumescent coating	5 mm steel	540	1.2	15	6.5

Table 1 : Specimen Details

Notes :

a) All beams 135 mm wide;

b) The 30 mm plywood gusset comprised one layer of 12.5 mm (adjacent to the glulam surface) and one layer of 17.5 mm construction plywood specified as complying with NZS 3614 (SANZ, 1971) with a moisture content of 11 %. The two layers were glued together using resorcinol glue prior to fabrication.

c) The proprietary intumescent coating was applied at the maximum loading recommended by the manufacturer.

2.1.2 Furnace Temperature Measurements

The temperature of the atmosphere within the furnace was measured using twelve Type K chromel-alumel thermocouples, four 100 mm below the bottom edge of each test beam and distributed within the furnace as shown in Figure 1a.

2.1.3 Beam Temperature Measurements

Each beam in test FS1 had thirteen Type K chromel-alumel thermocouples to measure temperatures. Two disc thermocouples as specified in Clause 4.1.4 of ISO 834 (1975) were located in the joint between the gusset and protection and another two between the glulam and the gusset.

Three quicktip thermocouples were located in the joint region and six were located away from the joint, these being embedded 45 and 67.5 mm into the beam timber (Figure 4a). For the beam thermocouples, the hot junction was inserted into a 2 mm diameter hole predrilled in the timber, glued to ensure that it remained in position and the hole filled with epoxy sealant.

In addition for test FS1, beam PG2 had four, while beam PG1 had two quicktip thermocouples installed for measuring the nail tip temperatures. A 20 mm diameter and 67.5 mm deep hole was first drilled at the specific nail location from the opposite face. After the nail was driven from the other side, the hot junction of the thermocouple was wound around and glued to the nail tip. The enlarged hole was then packed with a mixture of sawdust and resorcinol glue.

In test FS2, two additional disc thermocouples were placed between the gusset and the protection and another two outside the protection for joint PG3. The thermocouples embedded 67.5 mm into the timber outside the joint in test FS1, were embedded 45 mm in test FS2 (Figure 4b). All thermocouple wires exposed to the furnace were protected with ceramic sheathing and ceramic couplers were provided where splicing was required. All the thermocouples were connected to a computer controlled data logging system which sampled the temperatures at thirty second intervals.

2.1.4 Deflection Measurements

Each beam had four linear voltage displacement transducers (LVDT's) measuring vertical deflections at midspan, at each end of the joint, and between the joint and the support on one side (Figure 1a). All the LVDT's were connected to a computer logging system which printed the deflection at 60 seconds intervals.

Vertical deflections outside the furnace were obtained using a ruler to record the levels of the beams and comparing them to those before the concrete masses were applied. These readings were taken at 1 metre beyond the point of load application at 5 minute intervals.

In test FS2, vertical deflections outside the furnace were obtained by using a theodolite to read the levels of the beams and comparing these to the levels of the beams before the loads were applied. These readings were taken at the point of load application, also at 5 minute intervals.

2.2 Results

2.2.1 Test FS1 - 6 December 1988

Beam PG2 (the central beam) failed after 50 minutes and the test was stopped. After removal from the furnace 7 minutes later, a fracture was observed about midway between one support and the protected joint. The initial fracture did not appear to have involved the uppermost (tension) laminations. All the exposed beams were heavily charred away from the protected joints. The lateral bracing restraints were also heavily charred.

Joints PG1 PG2, PG4	(Plywood gusset - two layers of 'control' board protection) The outer of the layers of 'control' board was removed easily. The inner layer was unaffected by the heat and the screws fixing this to the plywood gussets remained intact. The plywood gussets were not charred (Figure 5a) although charring occurred as a result of the chimney effect at the 20 mm gap between the ends of the two glulam beam members (Figure 5b). There was no visible nail slip on the gussets.

2.2.2 Test FS2 - 15 December 1988

Beam SG2 failed at 53 minutes and the suspended weights on this beam were removed. The test continued to the 60 minutes target time without further failures. After removal from the furnace four minutes later, beam SG2 was observed to have a fracture about 1 m from the same support as for the fracture of PG2. The beams were all heavily charred. The single layer of 'control' board protection and the intumescent coatings fell off when water was sprayed on them. Contact regions between the beams and the lateral bracing elements were protected and had not charred.

Joint SG2 (Steel gusset - intumescent coating)
A 20 mm clear gap developed between the gusset and the glulam around the perimeter of the gusset, extending to 50 mm, where the glulam 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 (Figure 6a). The steel gussets themselves were also distorted and warped (Figure 6b). When a corner of the gusset was removed, an average char of 20 mm was observed beneath the plate. A gap of 40 mm had developed at the top of the beam butt joint. The width of the gap decreased across the depth of the beam to about 3 mm at the bottom.

Joint PG3 (Plywood gusset - single layer of 'control' board protection)
The single layer of 'control' board was still attached at the completion of the test. The plywood gussets were charred to a depth of 20 mm on the inner face (face towards the centre of the furnace) and 10 mm on the outer face (see Figure 1b). The outer layers of the plywood gussets had delaminated and surface cracks had developed (Figure 7a). Charring had also occurred along the top and bottom faces of the beam. This was more severe along the bottom face where the protection had fallen off. The nails, where charring had occurred, could easily be dislodged by hand from the beam and gussets (Figure 7b). Nail slips of up to 1 mm were estimated visually in the plywood gussets.

Joint SG1 (Steel gusset - single layer of 'control' board protection)
The steel gussets were not damaged and the charring of the joint was predominantly on the top and bottom faces of the beam where the protection had become detached (Figure 8a). When corner sections were cut from the gussets and removed, char had occurred to a depth of 6 mm on the inner face and 1 mm on the outer face of the glulam beneath the gusset. Nail slips of up to 1 mm were also estimated visually in the timber beneath the gussets (Figure 8b).

For the two outer beams (SG1 and PG3), measurements indicated that in each case the inner face of the beam had an average of 10 mm greater depth of char than that measured on the outer faces. This was consistent along the length and across the depth of the beam. Although there were variations in depth of char across the depth of the beam, there was no apparent correlation between char depth and the position of gluelines. The condition of the joints and the beams of test FS2 are shown in Figure 9.

Table 2 summarises the results of the full-size tests. Figures 10 to 18 show the temperature and deflections of these tests.

Joint	Temperature on glulam degrees C		Midspan deflection mm		Rate of midspan deflection mm/s	Average char depth on one face mm
	30 min	50 min	30 min	50 or 60 min	50 or 60 min (see sec. 2.3.2)	
PG1	25	50	18	44 (50 min)	2 (50 min)	-
PG2	45	105	13	48 (50 min)	5 (50 min)	-
PG3	50	120	12	47 (60 min)	3 (60 min)	15 (plywood gusset)
PG4	70	140	5	24 (50 min)	1 (50 min)	-
SG1	150 (25 min)		11	64 (60 min)	11 (60 min)	4 (glulam)
SG2	450	720	25	139 (53 min)	18 (53 min)	20 (glulam)

Table 2 : Summary of Full-size Tests Results

2.3 Discussion

2.3.1 Comparison of Furnace Temperatures with Standard Curve

Figure 10 shows the comparison of furnace to standard temperature time relationships for both tests FS1 and FS2. The severity, defined as the ratio of the area under the furnace temperature time curve to the area under the standard temperature time curve was 99 % for test FS1 and 103 % for test FS2.

In the initial stage, up to 15 minutes of test FS1, the furnace was smoke logged and there was insufficient oxygen to burn the fuel. It was therefore not possible to follow the standard time temperature curve for this period. Negative pressure was applied after this period to extract the smoke and allowed oxygen to enter the furnace. This resulted in more efficient combustion, and allowed the standard temperatures to be attained. Negative pressure was applied from the beginning of test FS2 which resulted in a slightly higher average furnace temperature. It should be noted that a positive test pressure would more realistically reflect a real fire and most standard test fires.

The average of the four thermocouples 100 mm below the beam, measuring the furnace temperatures indicated that in test FS1, the central beam (PG2) experienced a slightly higher temperature (Figure 11a). Figure 11b shows that the temperature 100 mm below the beam was slightly higher for SG1 than SG2, the central beam. Both of these figures show that beams PG1 and PG3 at the same location of the furnace were subjected to a lower temperature than the other beams. It should be noted however, that the PG3 temperature curve is comparable to the standard.

Figure 12 shows the temperatures on the protections of specimen PG3. The temperature of the protection facing towards the centre of the furnace was higher than that facing away. The average of the two temperatures followed the 'standard'

2.3.2 Failure Criterion

The failure criterion used to assess the performance of the protection methods in these full-size tests is that of 'loadbearing capacity', i.e. failure shall have been deemed to have occurred when the beam collapses or when a vertical deflection of 1/20 of span has been attained as outlined in BS 476 : Part 20 (British Standards Institution (BSI), 1987). Where a deflection of 1/30 of span has been exceeded, failure shall also be deemed to have occurred when the rate of deflection (in mm/min) calculated over 1 min intervals exceeds $L^2/9000d$ where L is the member clear span in mm and d is the member depth in mm. $L^2/9000d$ is equal to 4.2 and 3.6 mm/min for beam depths of 540 and 630 mm respectively.

AS 1530 : Part 4 (Standards Association of Australia (SAA), 1985) currently has the critical deflection of 1/30 of span or when the beam collapses as its 'structural adequacy' criteria. This code is currently being revised and it is understood that the revision will follow BS 476 : Part 20 recommendations.

2.3.3 Performance of 'Control' Board Protection

The joints with plywood gussets protected by two layers of 'control' board (beams PG1, PG2, PG4) remained fully functional. The surfaces of the gussets and the beam beneath were not charred during the 50 minutes of the test, and the subsequent 7 minutes of lesser heating when the specimens were removed from the furnace, before being extinguished. The latter is consistent with the observed beam surface temperatures beneath the gussets being significantly less than 300 degrees C (Figure 13a). These temperatures were also higher than that measured by Yiu and King (1989) at 50 min. It is suspected that this is due to the fully immersed specimens of the current series as opposed to immersion on one face of the specimens only in Yiu and King's tests.

The midspan deflections of the beams as shown in Figure 14a were steady, reaching 44 mm at 50 minutes.

Both the steel and plywood gusset joints protected by one layer of 'control' board (beams SG1, PG3) continued to carry their imposed load for the 60 min of standard fire exposure and were considered to achieve a 60 min FRR. Not withstanding, from Figures 14b and 15b it is apparent that the rate of increase of the vertical deflection and the rate of joint rotation of the steel gusseted joint (SG1) was increasing rapidly at the completion of the test. While the rate of deflection exceeded that permitted in BS 476 : Part 20 at 59 minutes, the total measured vertical deflection (1/75 span) was outside the range where this check is required to be considered (1/30 span). The rapid increase of the rate of joint rotation was also evident for the plywood gusset joint (PG3). This has been interpreted as an indication that there were low levels of reserve capacity in the joints by this stage.

The bending stress in the plywood gusset after the test was 23 MPa, based on the uncharred section of the gusset (as calculated in the Appendix). This result supports those presented by Jackman (1981) where he concluded that dense nailed plywood gussets have a predictable behaviour under fire. In his tests, the plywood did not fail until the thickness was reduced by charring to a point where the stress in the gusset was close to the ultimate strength of the cold material. However, unlike his study which did not show nails losing their anchorage, this present series did (Figure 7b).

2.3.4 Performance of Intumescent Coating

Although the failure of beam SG2 was remote from the joint after 53 minutes and the furnace environment was more severe than the standard, the condition of the joint following the completion of the test (60 min), was such that its ability to carry the load up to 60 min is considered doubtful.

Figure 13b shows that the glulam beneath the gussets began charring after 15 minutes of the test, assuming the 'onset of char' temperature of 300 degrees C. At the time of failure, the deflection at the joint was 139 mm and was increasing rapidly (Figure 14b). The rate of deflection limitation was exceeded at 44 min and it was likely that the limiting vertical deflection of 1/30 of span (150 mm) would be reached before 60 minutes and hence failure. The joint rotation as shown in Figure 15b is also significantly higher than the rotation of the joints protected with one layer of 'control' board.

The 35 mm edge distance allowance of charring (above and below the gussets) was inappropriate because the fire attacked the glulam from the faces as well as from the top or bottom surfaces (Figure 16a). This design was not able to prevent the nails from being exposed to furnace conditions with charring penetrating to the second row of nails. Moreover, a path was provided where the fire attacked the glulam beneath the steel gusset as well as the steel gusset itself.

Better detailing to improve the performance of intumescent coating protection would be to increase the depth of the gussets to cover the full depth of the beam, and increase the end and edge distances of the nails so that charring of the timber around the nails is avoided (Figure 16b). The performance of the joint may also be enhanced by applying an intumescent coating for wood members, to the timber around the steel gussets and to the top and bottom faces of the beam (White, 1988b), thereby delaying the onset of char by about 17 minutes (Nullifire Limited). This is approximately equivalent to half-an-hour of normal charring of wood (Buchanan, 1987), but this method is not recognised by the New Zealand Codes.

2.3.5 Comparison of Plywood and Steel Gussets

Both members PG3 and SG1 exhibited similar deformation characteristics up to about 53 minutes as shown in Figure 14b. At 60 min, the vertical joint displacement of PG3 was 47 mm compared to 64 mm for SG1 (Table 2).

The beam surface temperature beneath the steel gusset was higher than beneath the plywood gusset using one layer of 'control' board protection. This is consistent with plywood gussets being better insulators than steel gussets.

Joint rotations can also be compared (Figure 15a) using the following assumptions :

1. Both plywood and steel gussets remained rigid throughout the test and the plate orientation was defined by LVDT points D3 and D5;

2. The beam sections within the joint remained rigid throughout the test;

3. The vertical deflections measured were those of the upper beam surface throughout the test;

4. The joint rotation was from the nail slips caused by the higher temperature at the constant moment.

The plot of joint rotation against time (Figure 15b) indicates that the joints performed similarly throughout the test, with the steel gusset being slightly more rigid. It should be noted that the joint rotations plotted are those due to the effects of higher temperature only and not the effects of the applied moment.

2.3.6 Effect of Position within Furnace

In both tests, failure occurred in the central member remote from the protected joint towards the same end of the furnace. In test FS1, the central beam was at a lower level of stress than one outer beam which did not fail.

The average furnace temperature measured 100 mm below the central beam in test FS1 was slightly higher than that below the two outer beams, while in test FS2, this temperature was only higher than that below one outer beam (Figure 11).

Hall (1968) tested four glulam beams using a gas-fired furnace of the same width but of a shorter length and concluded that the two outer beams were more resistant due to slightly different heating conditions. Hall's test subjected the beams to a uniform loading regime, with full lateral support of the compression flange through contact with the loading surface. The predicted failure time of his test was 43 minutes assuming a charring rate of 0.64 mm/min, with actual failure of the first beam in the central position, occurring at 53 minutes when the test was stopped.

It is postulated that in the present tests, when the outer beams commenced charring, they acted as a source of radiation for the central beam (and vice versa) thereby consequently increasing the charring rate of the central beam 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 SG1 (facing towards centre of the furnace) was more rapid than those of beam PG3 facing away from the centre of the furnace (Figure 17b). Moreover, the inner face of joint PG3 was subjected to a higher temperature than its outer face (Figure 12). Thus it may be concluded that the central beams and the inner faces of the outer beams were subjected to a higher temperature environment and burned more rapidly due to radiation effects from the adjacent beams. 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. The emissivity between wood to wood is also higher to that between wood and concrete.

2.3.7 Effect of Different Beam Depths

The level of load applied to the member was dictated by the average nail stress. Thus as the member of greater depth was able to accept deeper gusset plates, the applied moment was increased to ensure that the average nail force remained at 1.2 x basic permissible.

The joint displacement of the 630x135 mm beam, which has a higher stiffness, was smaller than that of the 540x135 mm beam (Figure 14a, Table 2). There were no significant differences in temperature on the beam surface beneath the gussets up to 50 minutes (Figure 13a).

Whilst the beam stiffness is enhanced with increase in section depth, it is the width of the section which dictates the lateral buckling resistance of the member, particularly in a fire environment (see below).

2.3.8 Effect of Lateral Restraint

Failure of each central beam was thought to have been caused by lateral instability of the residual section of beam, and which may have initiated fracture of the compression flange remote from the joint. Lateral restraint mechanisms were provided to this flange in both tests. In test FS1, as the beams deformed upwards, the soffit of the beam at that point became exposed and charred, as did the faces of the restraint blocks, thus making the restraint ineffective. In test FS2, 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 beam width was greater than calculated, and could have resulted in lateral buckling occurring between the beam support and the restraint point.

The type of actual lateral restraint in real buildings needs to be considered carefully in each case. Timber purlins of smaller cross-sections, claddings and some other bracing devices may well become ineffective as lateral buckling restraints when subjected to a fire attack. Bracing utilising steel members would likewise become less effective with increasing temperature because of the reduction in strength and stiffness of steel. Furthermore, the steel bracing members could expand and instead of bracing the main member, could induce a lateral force causing premature failure. Particular attention should also be paid to the connection of bracing members.

2.3.9 Effect of Different Load Levels

Both beams PG1 and PG2 deformed steadily up to about 30 minutes but the lesser stressed central beam (PG2) deformed more rapidly after about 35 minutes resulting in its displacement being greater than that of the higher stressed beam (Figure 14a) at the completion of the test. 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. It should be noted that the changes in midspan deflection resulted both from joint relaxation with the increasing temperature, and a reduction in stiffness of the exposed member due to sectional changes with charring.

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 applied load. Rogowski (1967), from the same work concluded that there is no clear indication that load affects the charring rate at the 80 % confidence level. Ahlen and Mansson's (1979) work on steel gusset plates loaded only in shear concluded that the rate of burning increases in proportion to the load when this is transferred to the timber by uninsulated steel.

Nevertheless, with only one beam tested here at the higher stressed level, the effects of different load levels is inconclusive.

2.3.10 Estimate of Glulam Charring Rate

The thermocouples, embedded 45 and 67 mm into the beam, were installed into holes drilled from the side of the beam. The thermocouple wires were thus crossing isotherms developed within the timber section. Moreover, it was considered not practical to shield these wires within the timber, and they may therefore have been exposed to furnace temperatures following the onset of charring. The wires would thus have provided a heat path to the thermocouple junction which would have resulted in temperature readings of the furnace conditions, rather than that of the timber at those depths.

The charring rate of the exposed sections of beams was estimated by considering the temperature of the thermocouples embedded 45 mm into each beam of both tests with the assumption that the 'onset of char' coincided with a temperature of 300 degrees C. This occurred after an average time of 39 minutes resulting in a char rate of 1.15 mm/min. This char rate is much higher than the currently accepted value of 0.6 mm/min as recommended in MP9 (SANZ, 1987). The fact that the exposed sections of the central beams failed before the test time of 60 minutes confirmed a higher rate of char than expected (refer Appendix A).

It has been discussed previously that the central beams and the inner faces of the outer beams of both tests were subjected to a more severe time temperature regime than required by the standard (ISO, 1975). If the thermocouples in the outer faces of the outer beams were considered only, an average time of 53 minutes (4 thermocouples considered) elapsed for char to penetrate the 45 mm giving a char rate of 0.84 mm/min. This value of 0.84 mm/min correlates well with that recommended by the American Institute of Timber Construction (AITC, 1985), where a charring rate (in mm/min) of 360/S is recommended, S being the dry timber density in kg/m^3. The average dry density of the beams tested (at 12 % moisture content, ovendry density of 460 kg/m^3) was 411 kg/m^3 which implies a char rate of 0.88 mm/min according to the AITC formula.

On the other hand, White (1988a) carried out tests on eight species of wood to develop empirical models for the charring rate. An evaluation of the two models recommended by White shows that the average rate of char decreases as the depth of char increases. The char rate of solid pine at a depth of 45 mm, 12 % moisture content and density of 460 kg/m^3 is predicted to be 0.6 mm/min at 60 minutes.

2.3.11 Performance of Nails

The nail tip temperatures reached 130 degrees C after 50 minutes (Figure 18), significantly higher than those recorded by Yiu and King (1989). This is consistent with the more severe heating conditions with the beam fully immersed within the fire (cf. fire attack from one face only). Thermocouple T17/PG2 reached 350 degrees C after 50 minutes and was rapidly increasing. This thermocouple was installed near the edge of the gusset protection and may have been affected by heat which was conducted from the exposed sections of the beams.

Within the beam beneath the intumescent coated steel gussets, charring of the timber occurred around the nails. The nails exhibited a double curvature behaviour with full fixity of the nails occurring in the steel gussets. They also deformed tangentially to the centre of rotation of the nail group in accordance with classical theory.

2.3.12 The Member Butt Joint

In test FS1, there was a 20 mm gap at the joint between the members such that the full moment was transmitted between members via the gusset plates and not by direct bearing between beams (Kivell et al, 1982). On completion of the test, the bottom protection of the beams fell from the soffit during quenching. The gap acted as a chimney and, as a result of heat buildup in this area, continued to burn (Figure 5b).

All beams in test FS2 were nominally in contact. However, a gap of about 5 mm was noted at the top, but no gap at the bottom, in beam SG2 (intumescent coating) as a result of the non square ends of the beams.

Following the test, this had increased to a 40 mm gap at the top, decreasing down the depth of the member to around 15 mm at the bottom.

Aarnio and Kallioniemi (1979, 1983) observed that when the gap was wider than 5 mm, the timber changed into charcoal across the full width of gap and the corners were rounded off, regardless of the width of the test beams and the duration of the test. Kordina and Meyer-Ottens (1983) recommended that gaps between beams, or between beams and columns should be less than 3 mm wide. It would be appropriate to limit the gap in joints to 3 mm when using intumescent coating protection. If fire penetration into the joint is undesirable, the joint could be filled with intumescent coating on the timber members.

2.3.13 Joint Geometry

The joints in the tests were made up of straight beams butted together and loaded in bending only. To make up a joint with geometry representing either a knee or apex joint of a portal frame and be tested in the furnace was considered to be impractical and was therefore not attempted. The presence of a shear force as occurs in these joints, would have increased the design load of these joints in the no-fire environment, but overall, the load level of the nails in these joints in a fire environment would be the same. This is because the increase in nail load due to the presence of a shear force will be considered in design.

Portal action is primarily that of a flexural system whereby shear forces and shear deformations are small and often ignored. The results of this study are applicable to portal frame joints provided that the detailing of the protection is the same as that tested, i.e., totally protected with no joints in the protecting material.

2.3.14 'Control' Board Protection Fixings

Golding (1984) stated that the manner of securing protections to a joint plays a vital role in offering good fire protection. Yiu and King (1989) screwed the protection to the gusset/beam at 150 mm centres around the perimeter and also glued them to the plywood gusset. In the current series of tests, the same details as Yiu and King (1989) used to fix the protections were used. It was observed that some of the screws remained embedded in the gusset/beam even when the protections had fallen off.

Since the protections in these tests used full sheets without any joints, it is recommended that protections in knee and apex joints should follow the same detailing. This is because the behaviour of protections possessing joints has not been studied.

3.0 PILOT TESTS

The results from the full-size tests (FS1 and FS2) indicated that the beam/gusset rotation within the joints protected by a single layer of 'control' board were significantly lower than the specified limit (BSI, 1987; SAA, 1985). The load carrying capacity of the joints could therefore be related to the temperature of the components beneath the 'control' board (i.e. of the unloaded specimens). Chinniah (1989) worked out an example of a typical portal frame, based on nail slips from his simulated fire tests, and established that frame deformations due to nail slip (joint rotations) were much less than those due to charring of members. Hence, if the time temperature profile of the components beneath any form of protection were lower than that experienced by the 'control' board when subjected to the standard time temperature conditions, then the alternative protection could also be considered to provide the 60 min FRR to the joint.

Because full-size loaded joint tests are expensive, it was proposed that a comparative test method for other protection materials be developed using unloaded specimens suitable for a pilot furnace. Yiu and King's (1989) pilot tests results and their test method could not be applied because their tests subjected only one face of the specimen to the furnace, and it has been shown that full immersion of the specimen is required to adequately simulate the full-size test. Secondly, the criterion that was used to assess the performance of the joints of allowing no charring on the glulam beneath the protected steel gusset or the surface of the protected plywood gusset was too conservative.

It was anticipated that the proposed test method would be based on the time temperature development on the glulam surface for steel gussets and also the temperature beneath the protection for plywood gussets. Four unloaded plywood or steel gusseted glulam blocks protected with a single layer of 'control' board were therefore subjected to the 60 min standard time temperature conditions in the pilot furnace to obtain the time temperature relationships of the gusset beneath the protection, and of the glulam beneath the gusset.

3.1 The Experimental Programme

3.1.1 Test Setup, Method and Instrumentation

Two unloaded pilot tests (P1 and P2) were conducted using the 2.2 m high by 1 m wide diesel-fired pilot furnace at the BRANZ Fire Laboratory at Judgeford. Two double cantilevered specimens were tested each time. Infill concrete together with infill timber framed panels were used to seal the furnace and the time temperature conditions were again controlled as specified in ISO 834 (1975). The test arrangement, sample dimensions, and the thermocouple locations are shown in Figure 19.

The specimens were fabricated from the glulam lengths cut from the remnants of the full-size tests which had not been exposed to the furnace. They had an average moisture content of 11 %. One face of the 540x135 specimens had 30 mm plywood gusset while the other a 460x340x5 mm steel gusset. The 30 mm plywood gusset was fabricated by gluing 12.5 mm and 17.5 mm thick construction plywood together using resorcinol glue and had an average moisture content of 14 %. The 12.5 mm layer was placed adjacent to the glulam surface.

In test P1, both the top and the bottom specimens had the same gusset material facing the same side wall of the furnace. For test P2, the glulam lengths were reversed with the steel and plywood gussets opposite to their location in test P1 (Figure 19a). The tests were terminated after the specimens had been exposed to the furnace conditions for 60 minutes.

3.1.2 Furnace Temperature Measurements

The temperature of the atmosphere within the furnace was measured using four Type K chromel-alumel thermocouples, distributed as shown in Figure 19a.

3.1.3 Specimen Temperature Measurements

Each specimen had 15 stainless steel sheathed, Type K chromel-alumel thermocouples to measure the temperature. Five thermocouples were distributed between the glulam and the plywood or steel gussets. In addition, the face which was plywood gusseted had five thermocouples to measure the temperature between the gusset and the 'control' board protection.

3.2 Results

3.2.1 Test P1 - 26th July 1989

The single layer of the 'control' board protecting the plywood gusset deteriorated more severely than the one protecting the steel gusset. In addition to the burning off of the surface paper, this layer of board also cracked after 30 minutes. These cracks became much wider at the completion of the test. In the case of the steel gussets, only fine cracks appeared on the 'control' board.

The protection on the underside of the top specimen had already fallen off when the specimen was removed from the furnace, although all other protection remained (Figure 20a). This resulted in charring on the underside of the top specimen. Figure 21a shows the residual section of the specimens.

3.2.2 Test P2 - 28th July 1989

With the steel gusseted specimens turned around to face the other furnace side wall, the single layer of 'control' board protecting the steel gusset deteriorated more severely compared to the 'control' board facing the other wall. As with test P1, the underside of the top specimens fell off during the test. However, the end protection simulating a longer beam had been reinforced and remained intact (Figure 20b). Figure 21b shows the residual section of the specimens.

The glulam beneath the steel gussets which had begun charring showed clear and distinct patterns of the gluelines. It did not however indicate that there was any correlation between char depth and the position of gluelines (Figure 22a). Figure 22b shows the plywood gussets beneath the 'control' board of the top specimens of tests P1 (left) and P2 (right). The left specimen had charred and cracked more severely than the right.

In both tests P1 and P2, two minutes elapsed between the time the furnace was turned off and water being sprayed on the two specimens. Figures 23 to 28 show the temperature plots from the pilot tests.

3.3 Discussion

3.3.1 Comparison of Furnace Temperatures

Figure 23 shows that the average furnace temperature of both P1 and P2 tests (four thermocouples each) was comparable with the ISO 834 (1975) time temperature curve ('standard') and also to the average furnace temperature of test FS2. The severity of test P1 was 102 % while that of test P2 was 100 %.

Channel 0, the furnace thermocouple at the top, recorded the highest temperature for both P1 and P2 tests (refer Figure 19a for Channel locations). They recorded temperatures of about 100 degrees C greater than the 'standard'. In both tests P1 and P2, turning off the gas jet near Channel 0 did not reduce the temperature measured by this Channel. This was suspected to be the combined effect of the gas jet locations and the specimens setup in the furnace, obstructing and channelling the flow of gases and flames, resulting in a hotter side in the furnace. This hotter side was believed to be the cause of the 'control' board deteriorating more severely on one side in both tests P1 and P2.

Channel 1 and 3 temperatures were lower than the 'standard' for both P1 and P2 tests while Channel 2 was higher in test P1 but slightly lower than the 'standard' in test P2 (Figure 24). Notwithstanding, the thermocouple at the same location of the two tests recorded similar temperatures, within 100 degrees C, proving that repeatability of the tests can be achieved. Since the specimens were fabricated from combustible materials, i.e., glulam timber and gypsum plasterboard, this variation in furnace temperature is within the limits of ISO 834 (1975) which specifies a maximum deviation of any thermocouple of 200 degrees C.

3.3.2 Steel Gussets

The average temperature beneath the gusset (five thermocouples each) of the top and bottom specimens of test P1 was similar (Figure 25a). This correlation was also observed for the average temperature beneath the gusset of test P2 (Figure 25b). However, the average temperatures of the specimens of test P2 were higher than those of test P1 by about 150 degrees C at the end of the test as a result of being in the hooter side of the furnace.

The glulam temperature beneath the gusset of joint SG1 was measured for up to 20 minutes of the test at which time the thermocouples failed. Up to this time, the comparable temperatures observed in the pilot tests were similar. The charring on the glulam beneath the gusset for both top and bottom specimens of tests P1 and P2 was 2 mm and 5 mm respectively, as compared with 1 mm facing away from, and 6 mm facing towards, the centre of the furnace observed in joint SG1.

3.3.3 Plywood Gussets

The furnace environment adjacent to the plywood gusseted specimen (Channel 2 of test P1) followed the 'standard' curve closely (Figure 26a). In this regard, it was similar to joint PG3. Conversely, the furnace environment towards the top of the pilot furnace (Channel 0) was significantly hotter than the 'standard'. Despite this, the average temperature on the plywood surface beneath the 'control' board (five thermocouples each) and on the glulam beneath the gusset of both the top and the bottom specimens of test P1 was similar. A similar result was observed in test P2. As with the steel gusseted specimens, there was a 150 degrees C difference in plywood temperature beneath the 'control' board between tests P1 and P2 at the end of the test, the temperature being greater for test P1. This did not however, apply to the glulam temperature beneath the gusset where the average temperature of the specimens of tests P1 and P2 was very similar.

The temperature on the gusset beneath the protection of test FS2 was measured up to 40 minutes before the thermocouples failed. This was lower than the temperature of the specimens of test P1 but higher than the temperature of the specimens of test P2 while the glulam temperature beneath the gusset of test FS2 was higher than both tests P1 and P2. In addition to the glulam temperature, the gusset temperature beneath the protection should also be used as the basis for comparing the effectiveness of different protections because it is the residual section of the gusset which is transferring the load to the joint. The gussets had an average char depth of 20 mm in test P1 and an average of 10 mm in test P2. The plywood gussets of joint PG3 in test FS2 had a similar charring, i.e., 10 mm char depth facing away, and 20 mm facing towards, the centre of the furnace.

3.3.4 Comparative Test Method for other Protection Materials

The char depth of the glulam beneath the steel gusset and of the plywood beneath the 'control' board of tests P1 and P2 compared favourably and were similar to those of joints SG1 and PG3. Likewise, the measured temperatures of the glulam beneath the protected steel gusset and of the surface of the protected plywood in the pilot tests were comparable with those available for the full-size tests. These results indicated that the performance of the unloaded specimens in the pilot furnace was similar to the loaded full-size tests. A comparative test method for other protection materials is therefore viable, and can be developed using the temperatures obtained from these pilot tests.

While significant temperature variations were observed within both the pilot and the main furnace, it is important to note that these were within the limits specified by ISO 834 (1975).

It is recommended that comparative tests carried out in pilot furnaces of similar size to BRANZ's pilot furnace be limited to a single specimen located in the central zone of the furnace, thereby reducing obstruction within the furnace and minimising the influence of the specimen on the furnace gas flow patterns. Each specimen should have the same gusset and the same protection material installed on each face. The furnace should be driven to the 'standard' time temperature curve based on the average temperature of at least one thermocouple at 100 mm from each face of the specimen. Each steel gusset would need to have five thermocouples (as for the current pilot tests) to measure the temperature of the glulam beneath the steel gusset. For plywood gussets, an additional five thermocouples would be required to measure the temperature of the plywood gusset beneath the protection. The gusset details should be similar to those tested in the full-size loaded joint system, i.e., the plywood gussets should not be less than 30 mm in thickness, while the steel gussets should not have an air gap less than 10 mm between the gusset and protection.

4.0 FUTURE WORK

4.1 Charring Rate of Glulam

These tests indicated that the charring rate of the exposed sections of beams was higher than the currently accepted value of 0.6 mm/min given in MP9 (SANZ, 1987). Various possible causes of this discrepancy have been discussed within the report. Further tests are needed to establish the char rate for New Zealand glulam Pinus radiata.

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 and time. BRANZ currently has a research programme looking at the charring rate of glulam timber.

5.0 CONCLUSIONS

The following conclusions have been drawn from this study :

1. Nailed gusset connections can achieve a 60 min FRR when totally protected with a single layer of 'control' board. The results apply to boards with no joints constructed to the details used in these tests.

2. For the 60 min of exposure to the standard time temperature condition, there was no significant difference in the load carrying behaviour between the steel and plywood gussets protected by a single layer of 'control' board.

3. Significant temperature and radiation effects occurred in the main furnace and hence the location of the specimen within the test furnace significantly affected the performance of the joint.

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

5. The charring rate of the exposed glulam beams was estimated to be 0.84 mm/min, significantly exceeding the MP9 recommendation of 0.6 mm/min. This requires further study.

6. Because the performance of the joints in the full-size loaded joint tests is temperature and not deformation controlled, a comparative

test method to assess the performance of other protection methods can be developed using unloaded specimens in a pilot furnace.

7. The time temperature characteristics on the glulam beneath the steel or plywood gussets and on the plywood gusset beneath the protection have been measured. Comparative tests with different types of protection should be compared with these temperatures.

Appendix A

A.1 Code Recommendations

For commercial and industrial single storey buildings of Construction Type 4, Table 2 of NZS 1900 Chapter 5 (SANZ, 1984) specifies that one-hour FRR is required for structural frames when the separation distance to the boundary is between 1.5 and 6.0 m, and half-hour FRR when the separation distance is greater than 6.0 m.

MP9 (SANZ, 1987) recommends that :

a) timber structural members shall be capable of withstanding the design loads with:

   i) no earthquake load;

   ii) 2/3 of the wind load based on a five year return period gust speed, and;

   iii) no live load reduction for egress ways, 25% for storage occupancies and 50% for other areas;

b) for the purpose of fire resistance rating calculations, the basic working stresses listed in NZS 3603 (SANZ, 1981) to be multiplied by 2.0 and the load duration factors listed in that document shall not be applied to the allowable stresses;

c) a charring rate of 0.6 mm/min may be used for radiata pine (basic dry density 410 kg/m^3) and timber of species having approximately the same density. Charring shall be subtracted from all faces of beams/columns except where a floor/wall of equal or greater fire resistance is fastened to them.

A.2 Sizing of Test Beams

The beams were sized within the mid-range of portal frames typically used in New Zealand. From the Timber Use Manual (TIF, 1989), for a two-pinned gusset knee portal frame in glulam : light roof with ceiling, high wind area, eaves height 5 m and a span of 20 m, a 540x90 mm section is adequate for 4.7 m bays. This design is based on strength with no deflection limit.

For a one-hour FRR, MP9 (SANZ, 1987) recommends a minimum width of 115 mm, resulting in a Design Stress Ratio of 0.47 with 4 sides charred. The Design Stress Ratio is twice the ratio of the residual section modulus to the cold section modulus using a charring rate of 0.6 mm/min for a duration of 60 minutes. This minimum value of 0.47 was considered low for the tests and the beam section was consequently increased to 540x135 mm, resulting in a Design Stress Ratio of 0.62. To study the difference in performance of different beam depths, one beam had a 630x135 mm section, resulting in a more slender residual section.

A.3 Applied Loads

Since this work was primarily 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 (SANZ, 1981). Assuming that dead load = live load for a typical design situation and that under a fire attack no live load is present (Yiu and King, 1989), then the nail load under fire attack was determined at half the 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 level, the nails in beam PG1 were stressed to 1.8 times the basic load.

The MP9 (SANZ, 1987) recommendations of the 540x135 mm beam leads to an applied load of 45 kN-m for a duration of 60 min. The capacity of the residual section, when lateral buckling was considered, was 35 kN-m (see below).

A.4 Joint Loads

The basic load for a 3.15 diameter nail in shear as given in NZS 3603 (SANZ, 1981) is 214 N and for the 3.3 diameter gun nail using a linear approximation is 241 N in shear.

The minimum	spacing of nails along the grain	= 10 Da = 33 mm;
	across the grain	= 5 Da = 17 mm;
	minimum edge distance	= 5 Da = 17 mm;
	minimum end distance	= 12 Da = 40 mm.

For the steel gussets, the end distance of 20 mm was used.

a) Plywood Gusset
1100x540 gusset (Figure 27a):

edge distance = 50 mm; spacing along grain = 40 mm;
spacing across grain (staggered) = 30 mm;
number of rows, n = 3;
centreline dimensions of the nail group, rxq = 400x450;

p, weighted pitch = (11x40 + 16x30)/27 = 34 mm

Using the thin walled tube analogy : Mj = 2KFrqn/3p (TIF, 1989) where K is a constant depending on the aspect ratio of the nail group and the angle to the horizontal. The K factor (Walford, 1989) for a horizontal beam and an aspect ratio of 450/400, is 5.67 and therefore Mj = 3.8Frqn/p.

Mj = 3.8x (241x1.2)x 400x 450x 3/34 = 17 kN-m

$Mj = 26$ kN-m when the nails were stressed to 1.8 times the basic nail load.

1100x630 gusset : Using a similar pattern as the 1100x540 gusset;
$Mj = 3.8x\ (241x1.2)x\ 450x\ 460x\ 3/[(11x40 + 19x30)/30] = 20$ kN-m

b) Steel Gusset : 1100x470 gusset (Figure 27b)

$Mj = 3.8x\ (214x1.2)x\ 440x\ 390x\ 3/[(12x40 + 14x30)/26] = 15$ kN-m

A.5 Lateral Buckling

a) 540x135 section : after 60 min, Lay/B = 1500/63 = 23.8; D/B = 7.4 From NZS 3603 (SANZ, 1981), S1 = 17.9 and (from Table 7), K8 = 0.81. The Design Stress Ratio = 0.62 calculated from MP9 (SANZ, 1987).

Capacity of residual section, $M = 0.62x\ (540^2 \times 135/6)x\ 10.6x\ 0.81$
$= 35$ kN-m

b) 630x135 section : after 60 min, Lay/B = 23.8; D/B = 8.9, S1 = 19.6 and K8 = 0.73. The Design Stress Ratio = 0.66 from MP9 (SANZ, 1987).

Capacity of residual section, $M = 0.66x\ (630^2 \times 135/6)x\ 10.6x\ 0.73$
$= 46$ kN-m

A.6 Gusset Plates Design

In practice, knee joints will be designed for service load combinations. Furthermore, because of the geometry of the portal knee joints, the effective depths of the gusset will be greater than the depth of the sections and the stress in the gusset would be reduced considerably. Assuming that the dead load = live load, then the design moment of the gusset is 2 times the applied moment.

a) Plywood Gusset

540x135 section: M = 2x17 = 34 kN-m, F'b = 11.0 MPa, K1 = 2.0 (fire). To find the thickness, Z (Section Modulus) = $td^2/6$ = 34E6/(2x11); t = 32 mm or 16 mm each gusset. A 30 mm gusset was used on each side taking into account the orientations of the plies perpendicular and parallel to grain and also this is a typical size being used in real structures.
Actual gusset stress (Figure 28a),
$fb = 17E6/[2x(7\ \text{laminations})x2.5x540^2/6] = 10$ MPa.

After the test, 10 mm and 20 mm of plywood gusset remained (Figure 28b), therefore,
$fb = 17E6/[(2 + 5\ \text{laminations})x2.5x500^2/6] = 23\ \text{MPa} > 2x11 = 22$ MPa.

30 mm thickness gusset was also sufficient for the 630x135 mm section because although the applied load was slightly greater, this is offset by the bigger depth of the gusset plate.
Actual gusset stress, $fb = 20E6/(2x7x2.5x630^2/6) = 9$ MPa.

b) Steel Gusset

M= 2x15 = 30 kN-m
$Z = td^2/6 = M/fb$ = 30E6/(0.6x250); t = 5.4 mm or 2.7 mm each side. 5 mm gusset plates were used since this is the typical size being used in real structures.

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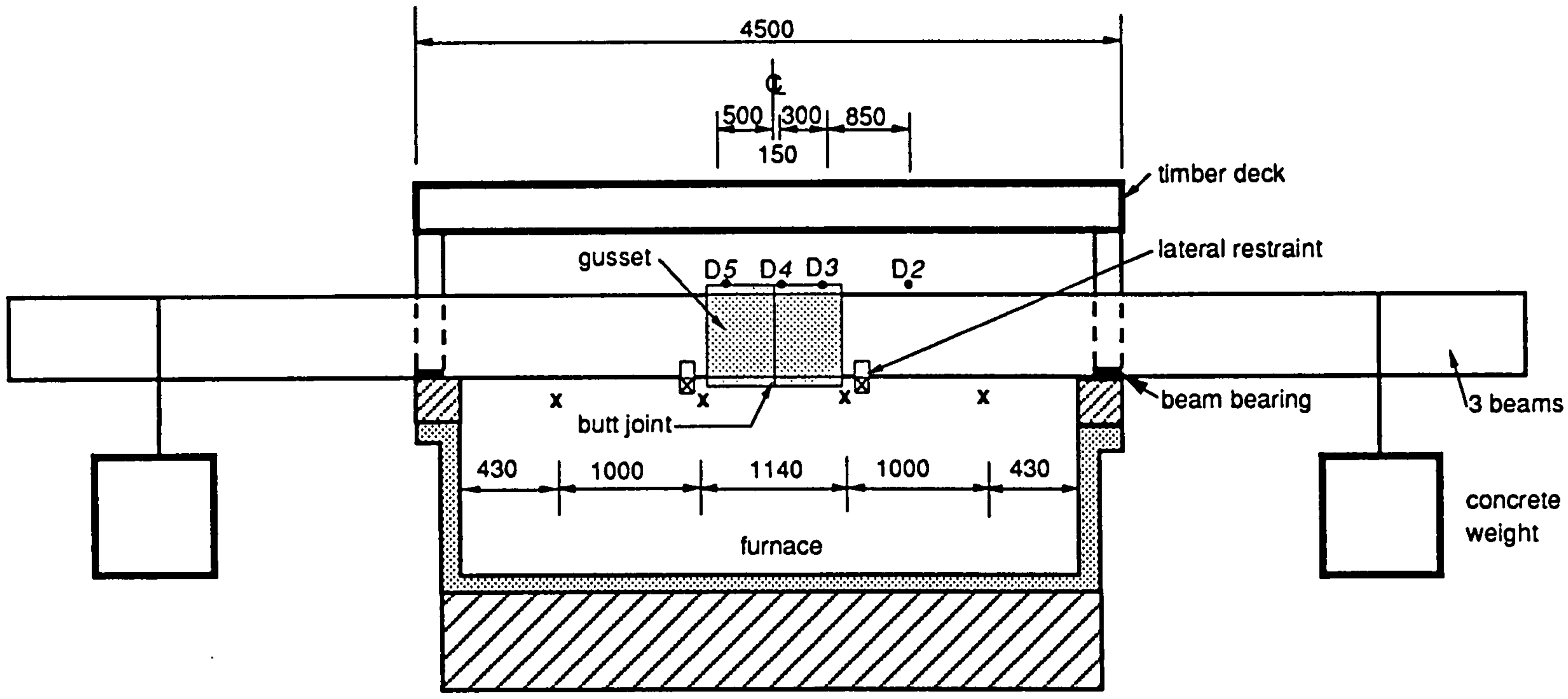


Figure 1a : Longitudinal Section and Deflection Reading Location
D*n* denotes a vertical deflection measurement point
x denotes thermocouples measuring furnace temperatures

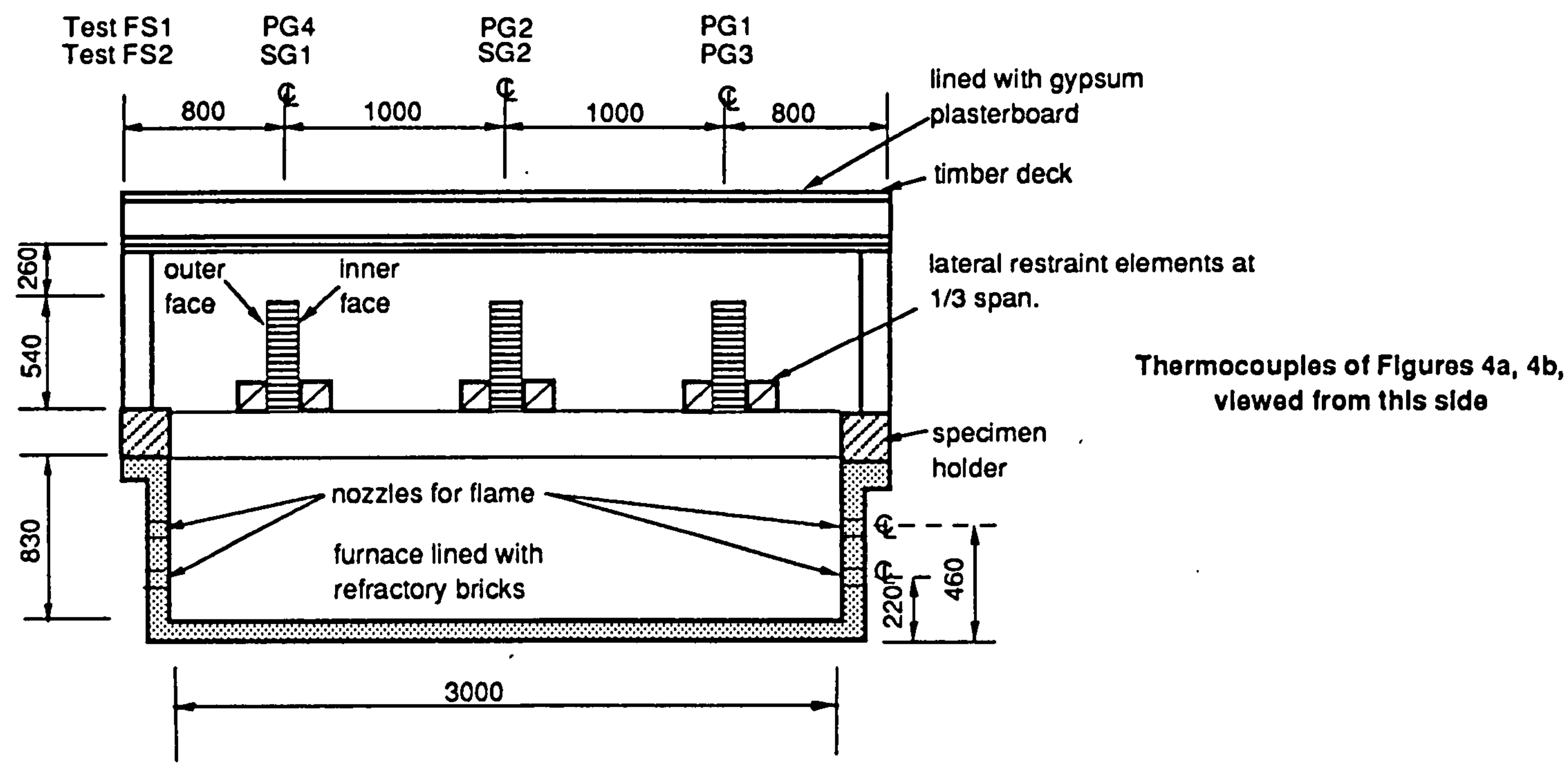


Figure 1b : Cross Section

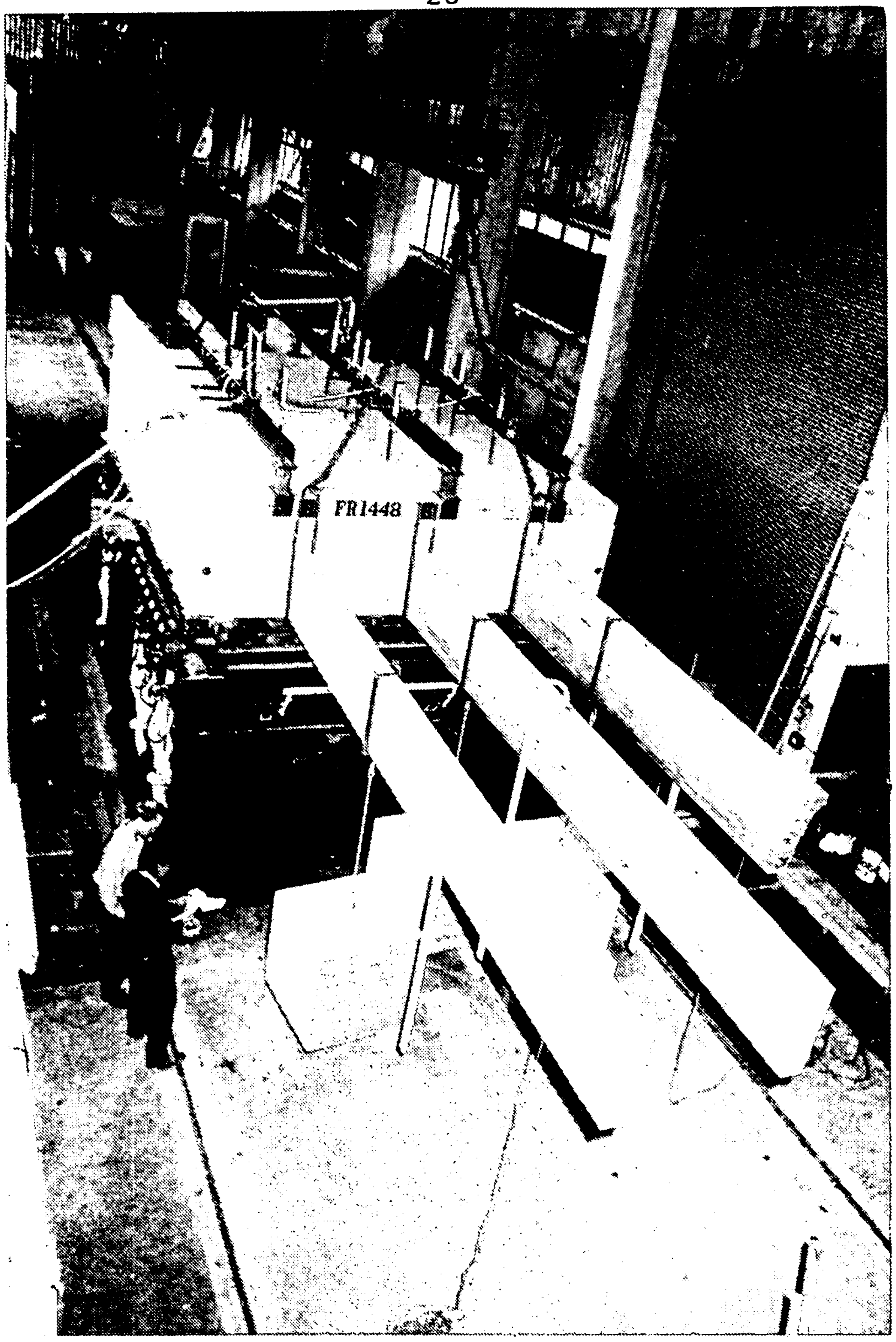


Figure 2a: View of test FS1

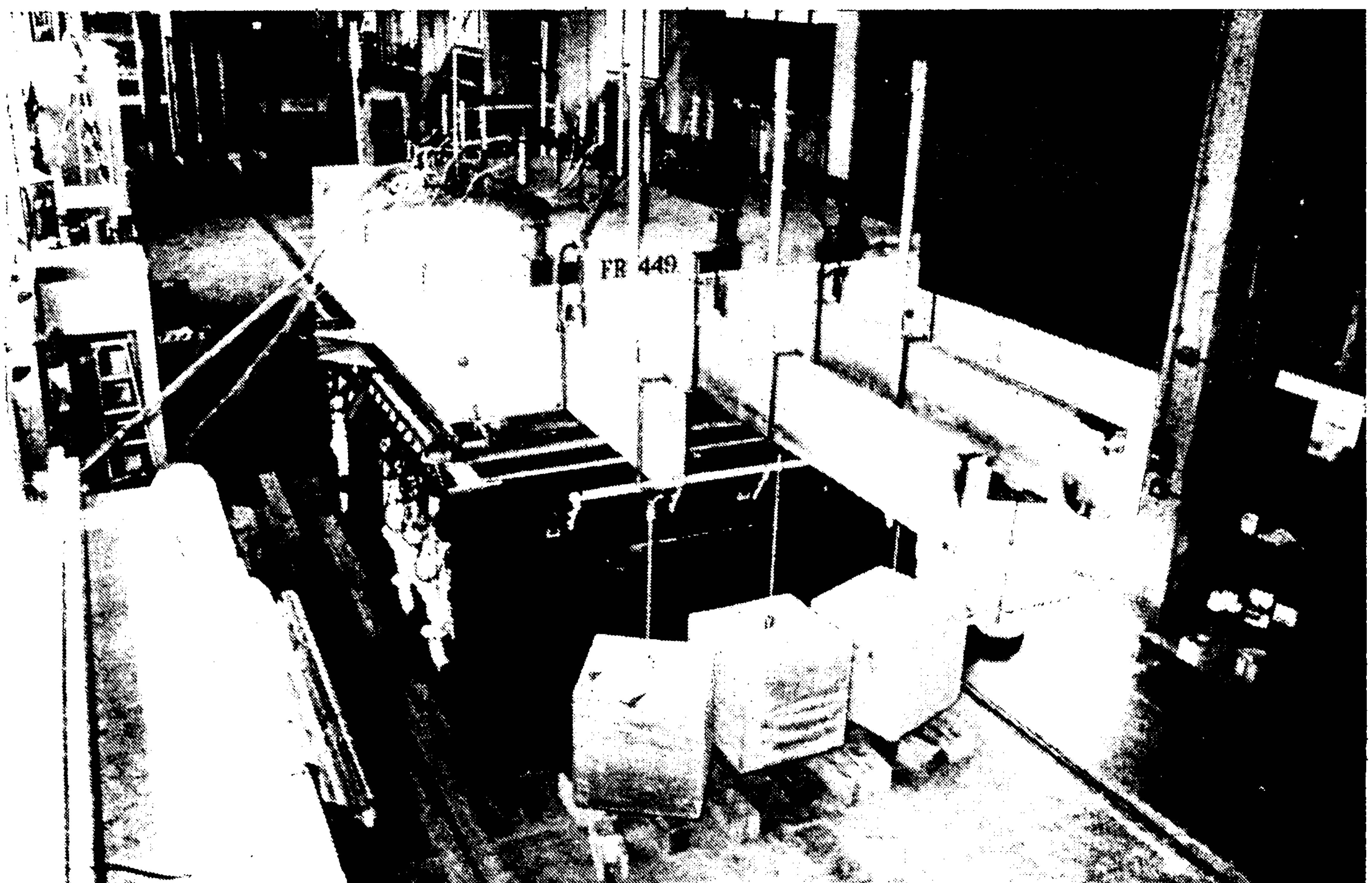


Figure 2b: View of test FS2

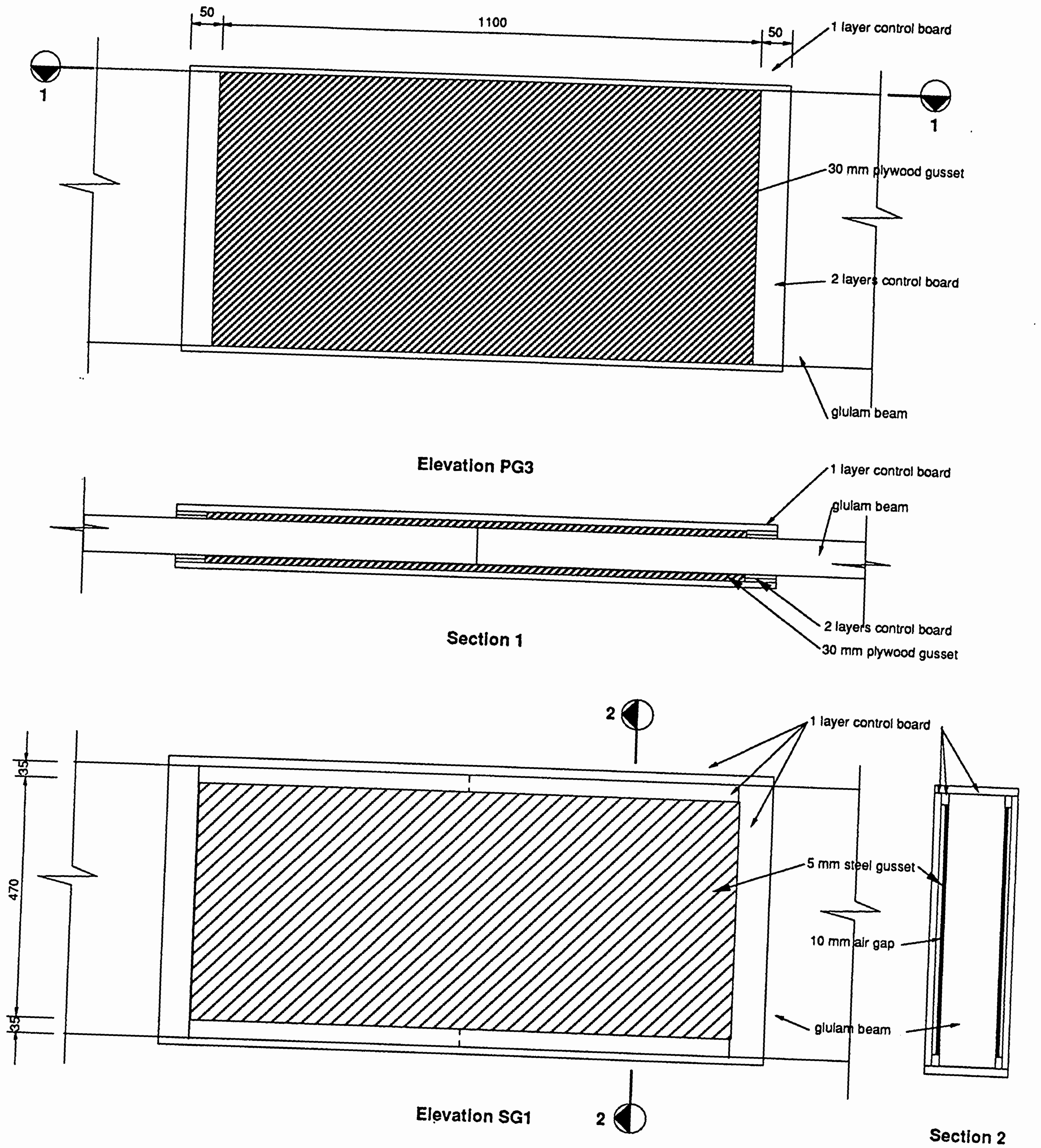


Figure 3 : Protection Details.
Protections screwed (at 150 mm crs.) using 32 mm gypsum screws, around the perimeter to the glulam and plywood gussets. Also glued using gib-fix to glulam and plywood gussets

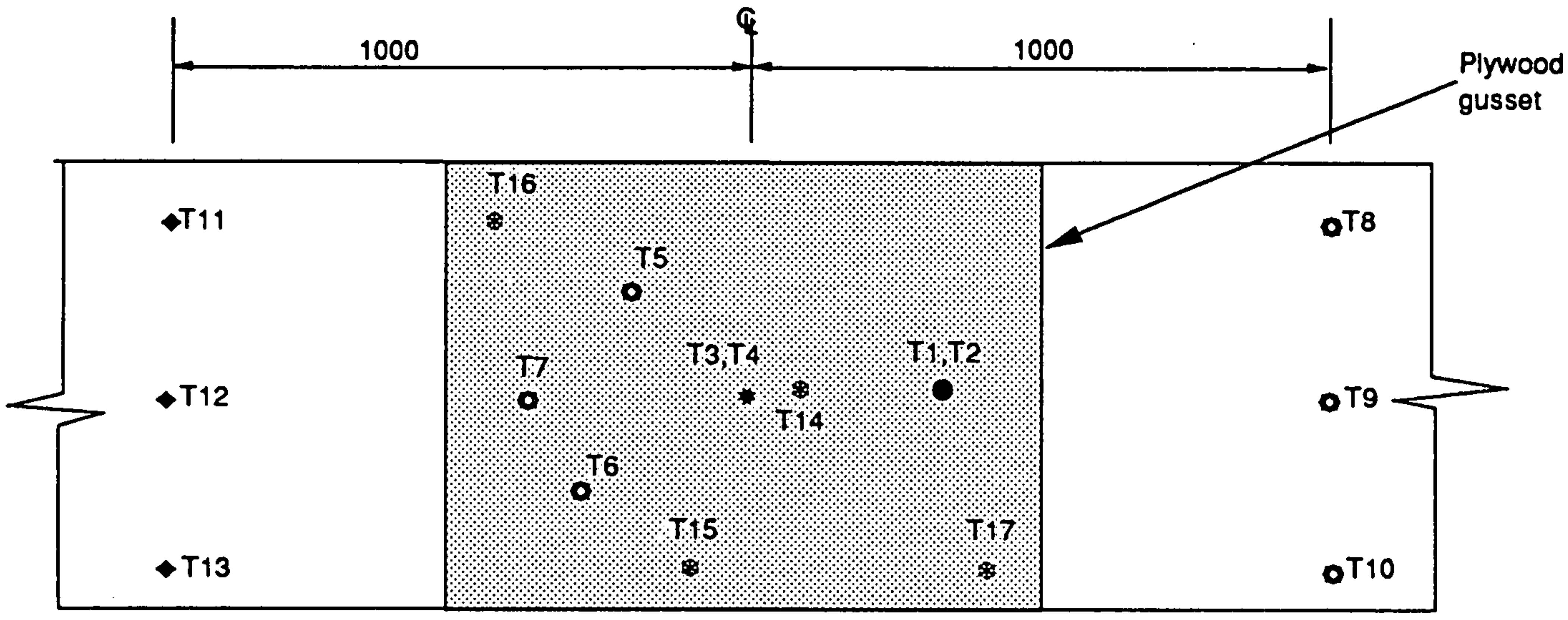


Figure 4a : Thermocouple Locations Test FS1

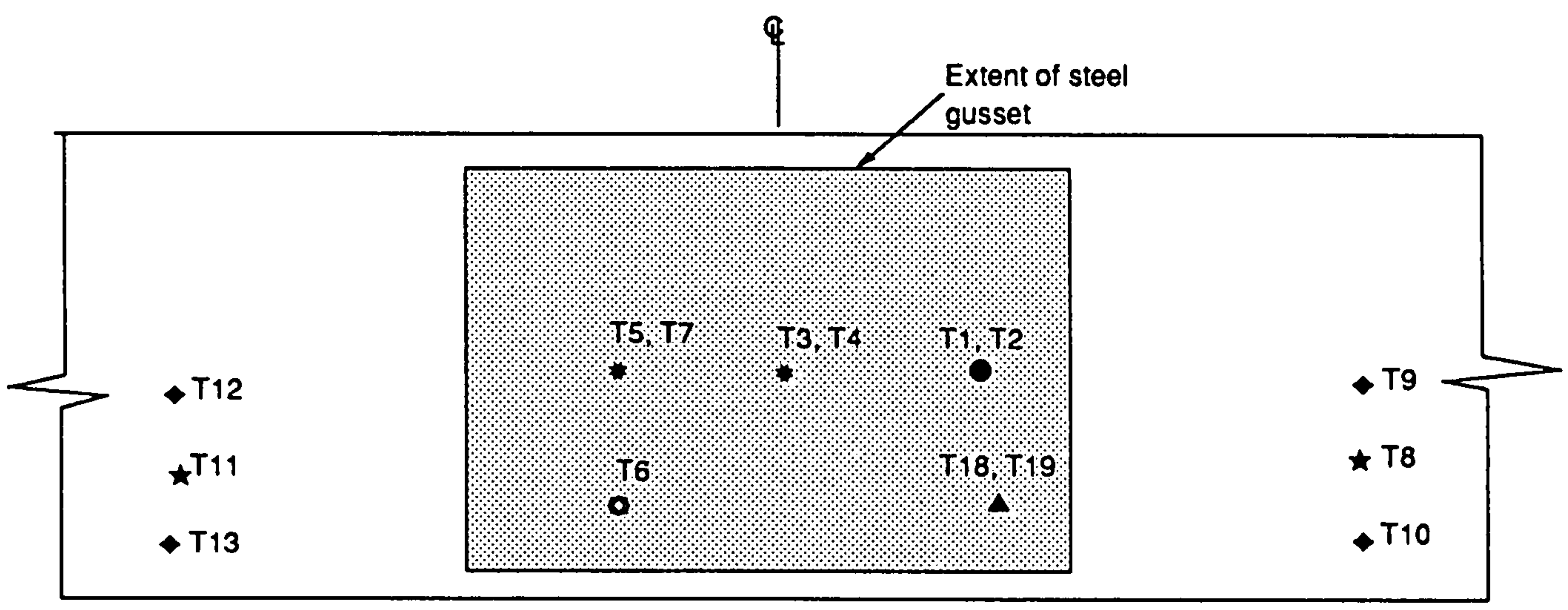


Figure 4b : Thermocouple Locations Test FS2

● between beam and gusset
✱ between gusset and protection (plywood gusset only)
○ embedded 67 mm into beam
◆ embedded 45 mm into beam, ★ far face
❋ at nail tip, T14, T15, - joints PG1, PG2 only
T16, T17, - joints PG2 only
▲ between protection and furnace - joint PG3 only (one on other face)
- Refer Figure 1b for orientation

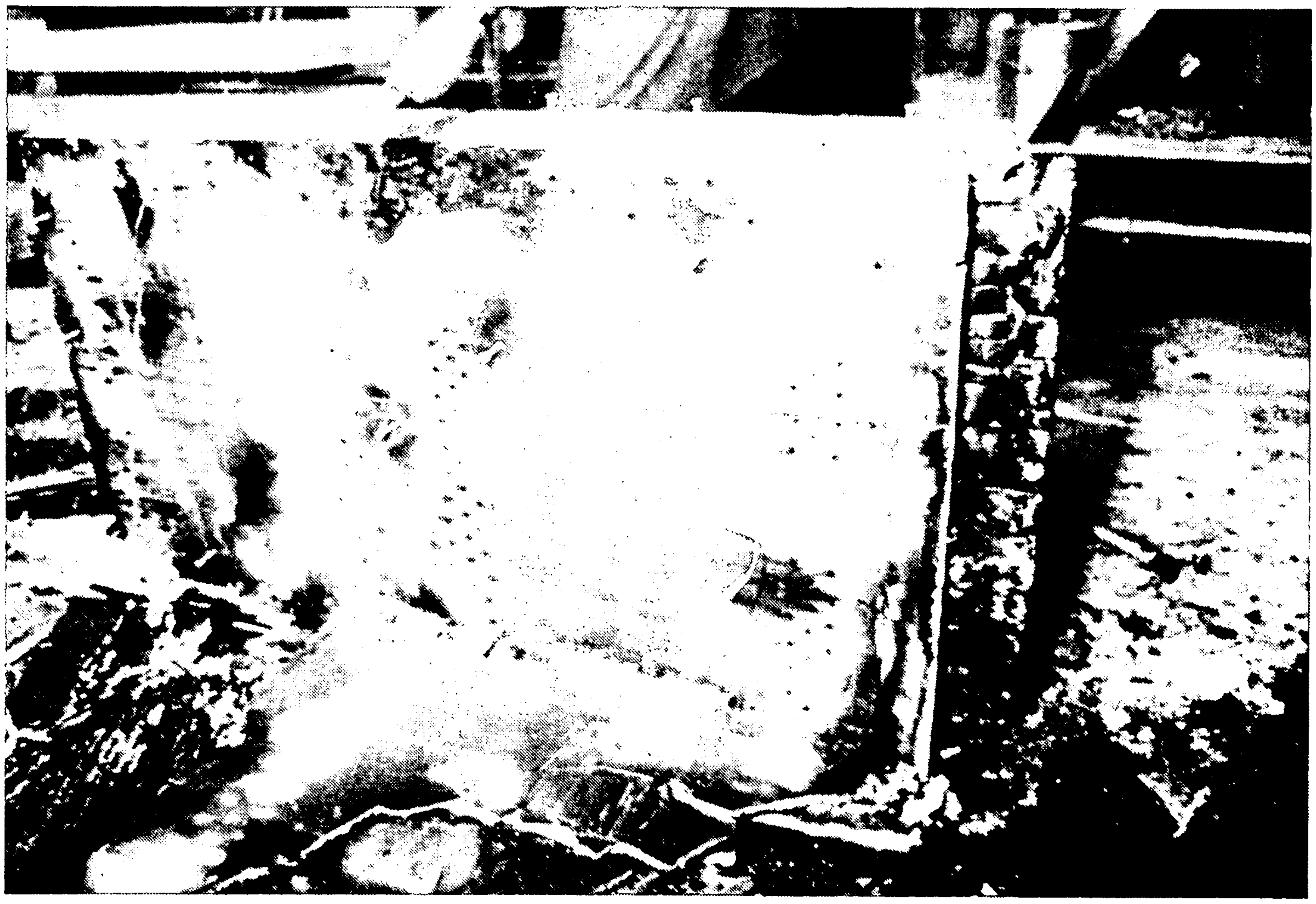


Figure 5a: Plywood gusset test FSI.

Figure 5b: Chimney effect due to 20 mm gap.

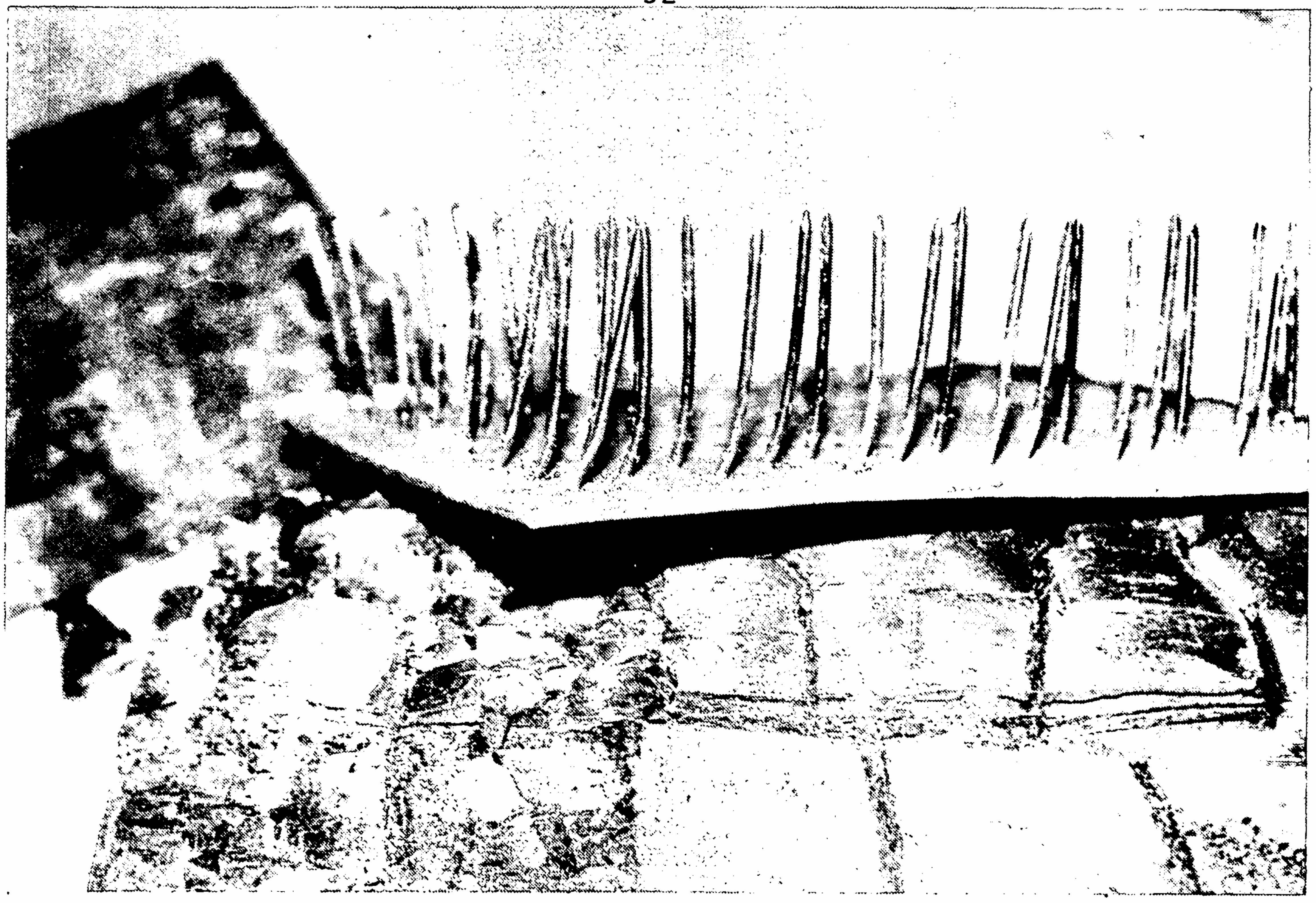


Figure 6a: Warping of steel gussets joint SG2.

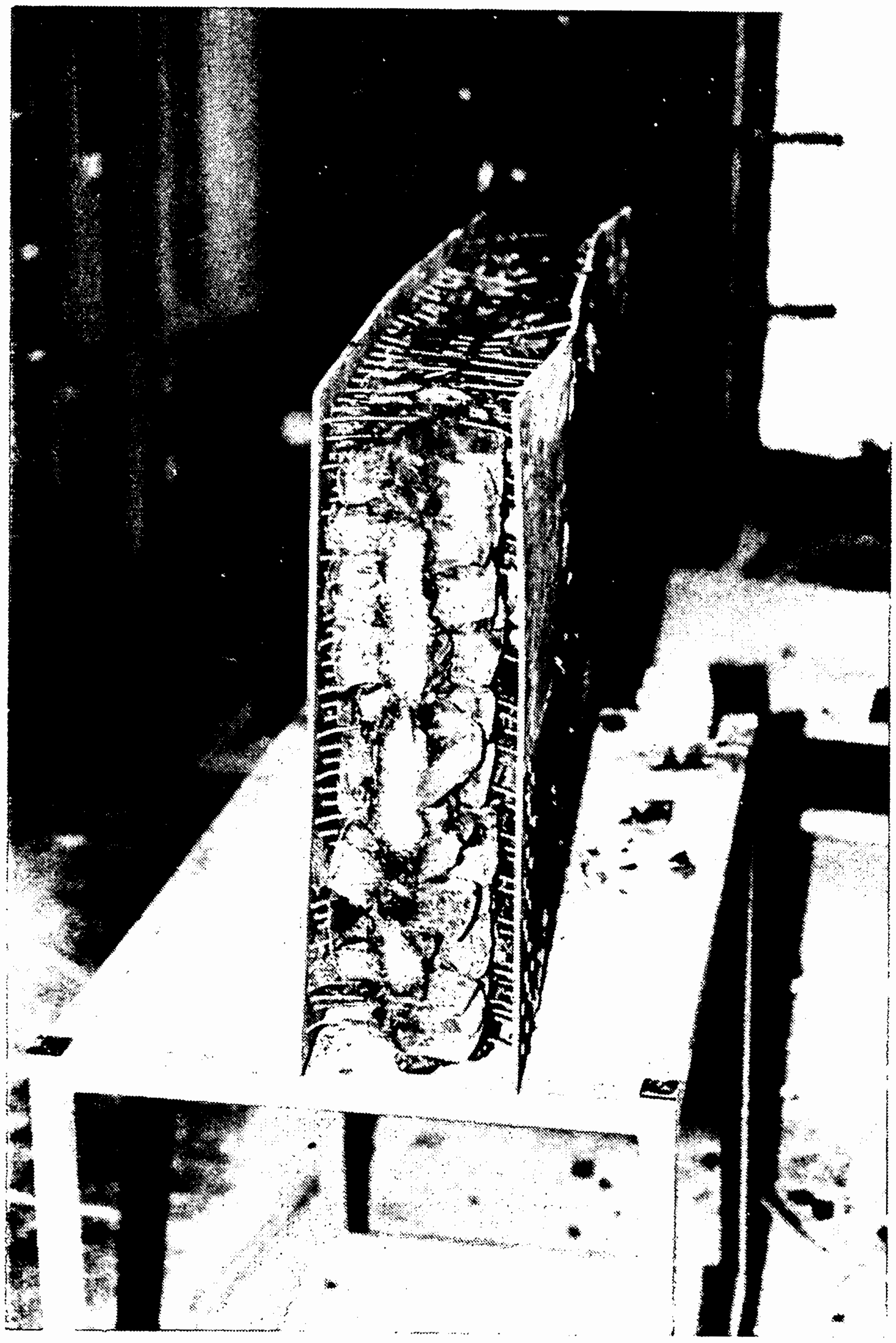


Figure 6b: Deformation of nails joint SG2.

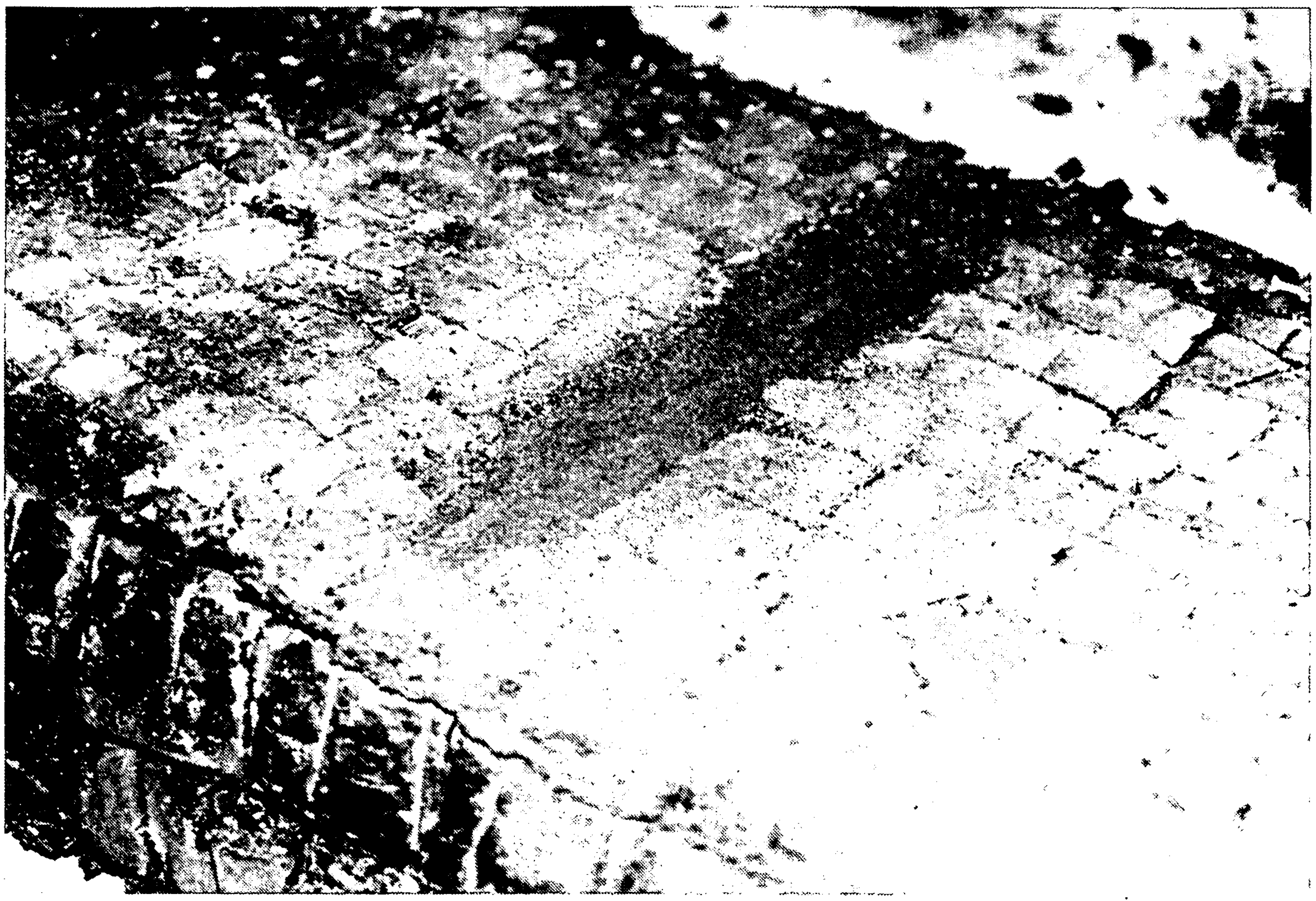


Figure 7a: Charring, cracking and delamination of plywood gusset, joint PG3.

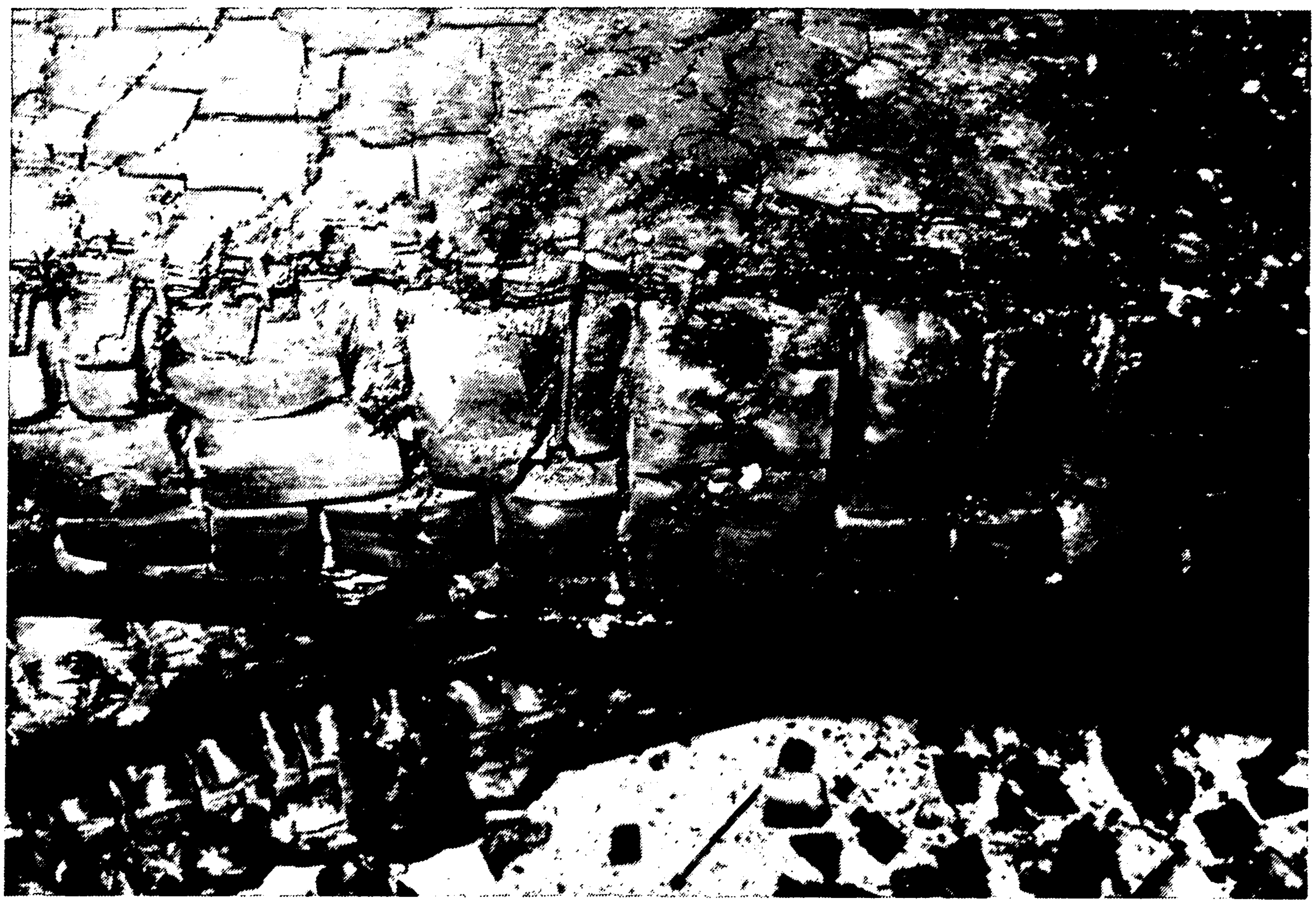


Figure 7b: Loosening of nails, joint PG3.

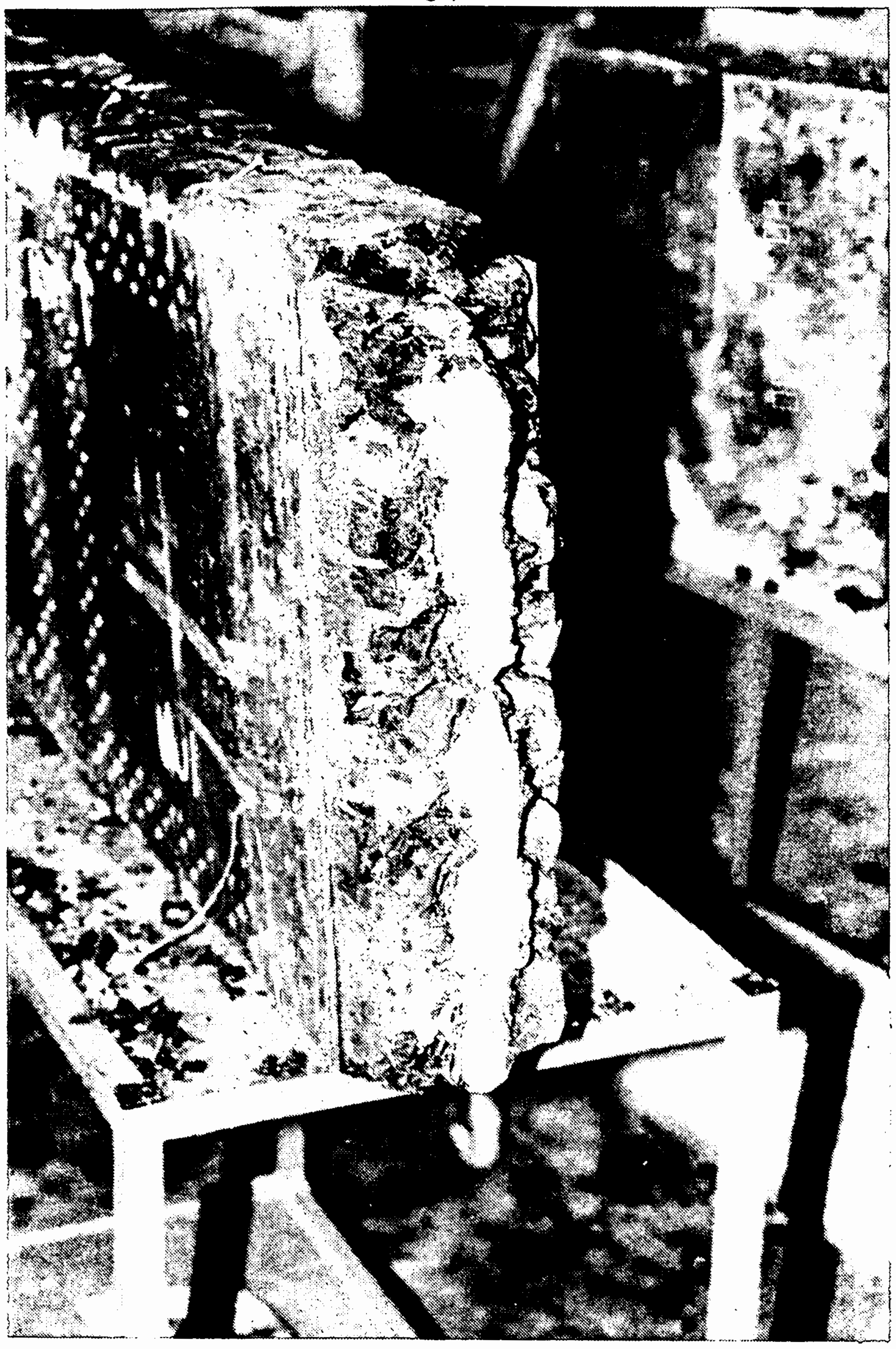


Figure 8a: Section adjacent to joint SG1.

Figure 8b: Charring of timber beneath steel gusset, joint SG1.

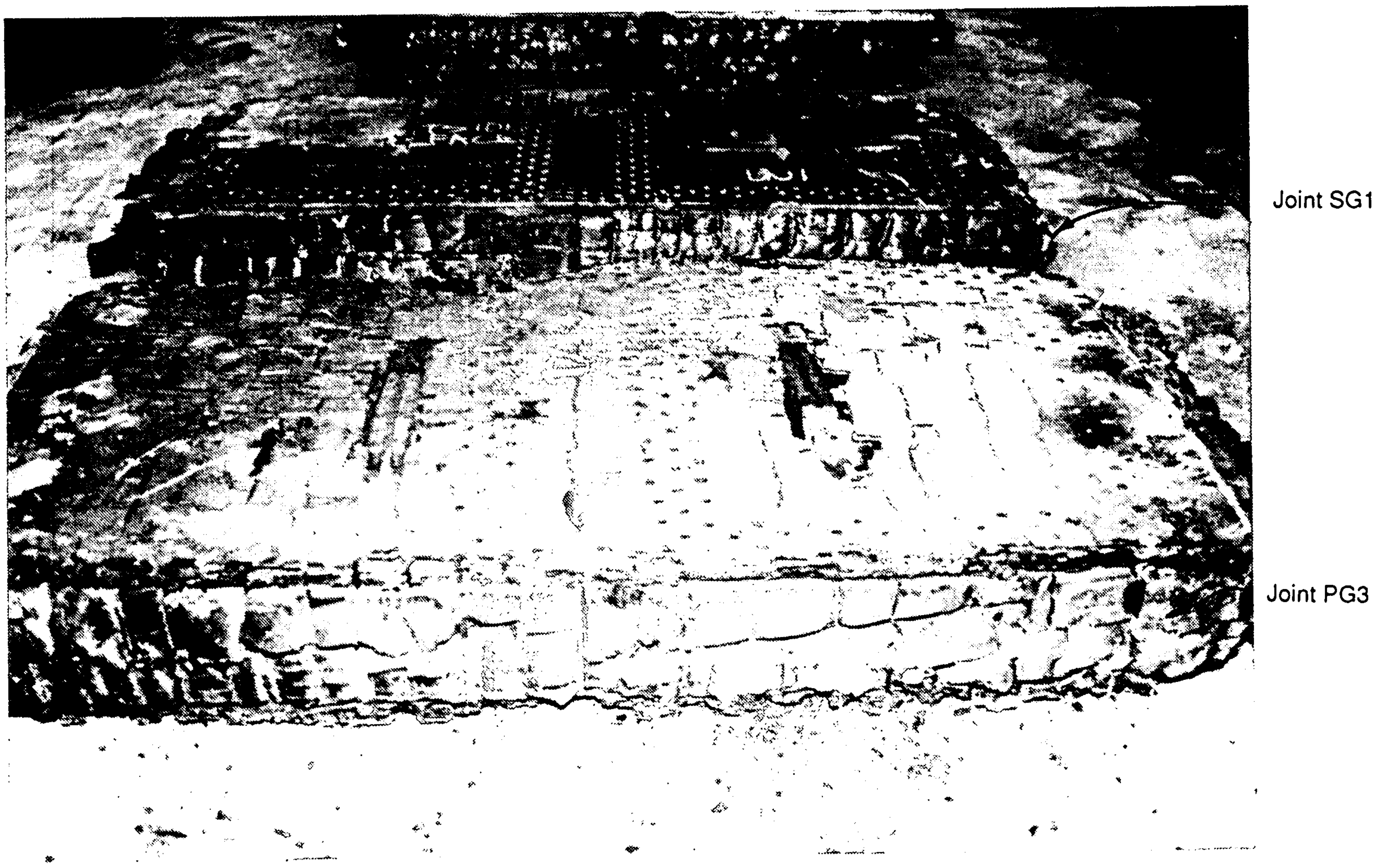


Figure 9a: Condition of joints after test FS2.

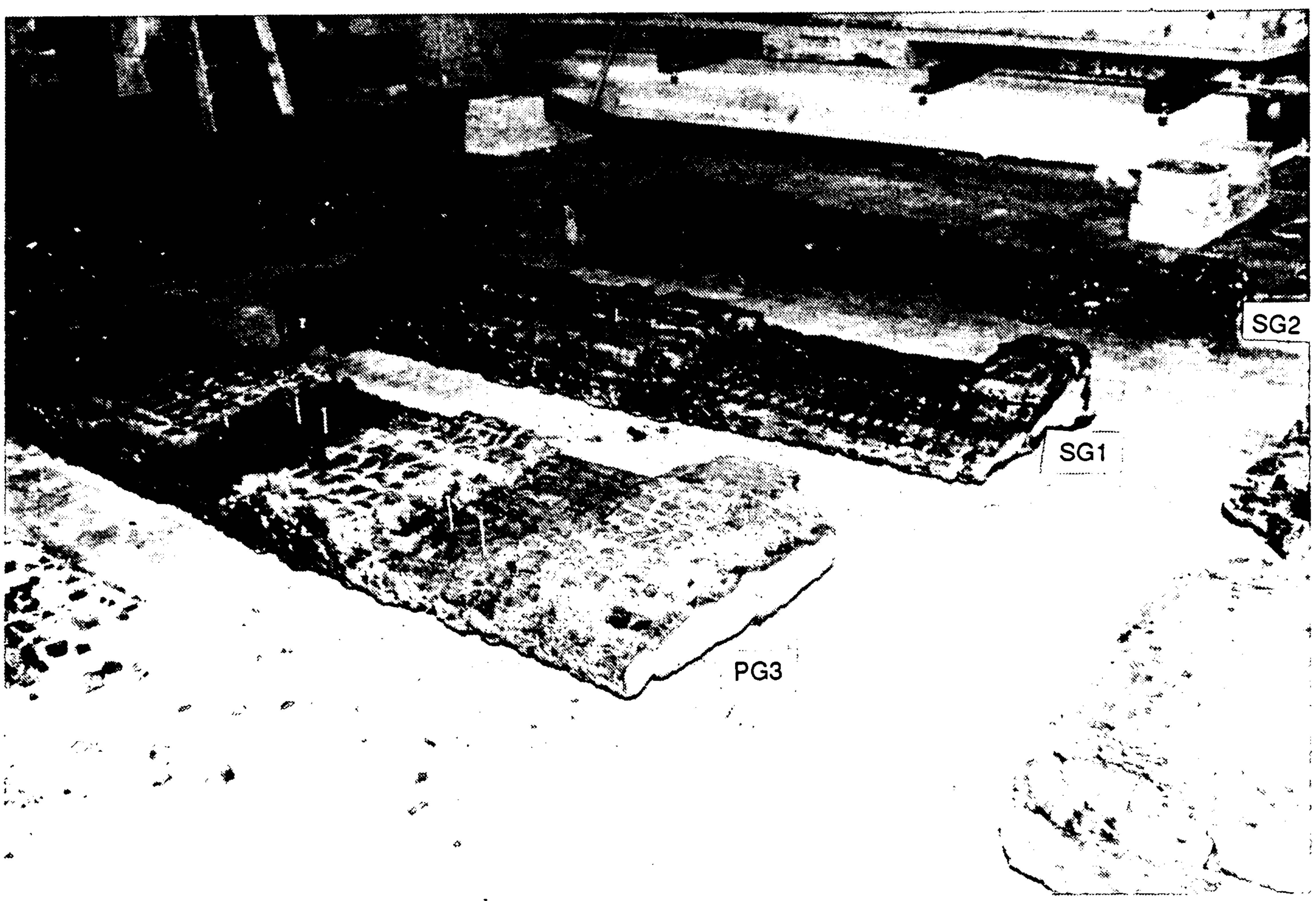


Figure 9b: Condition of beams after test FS2.

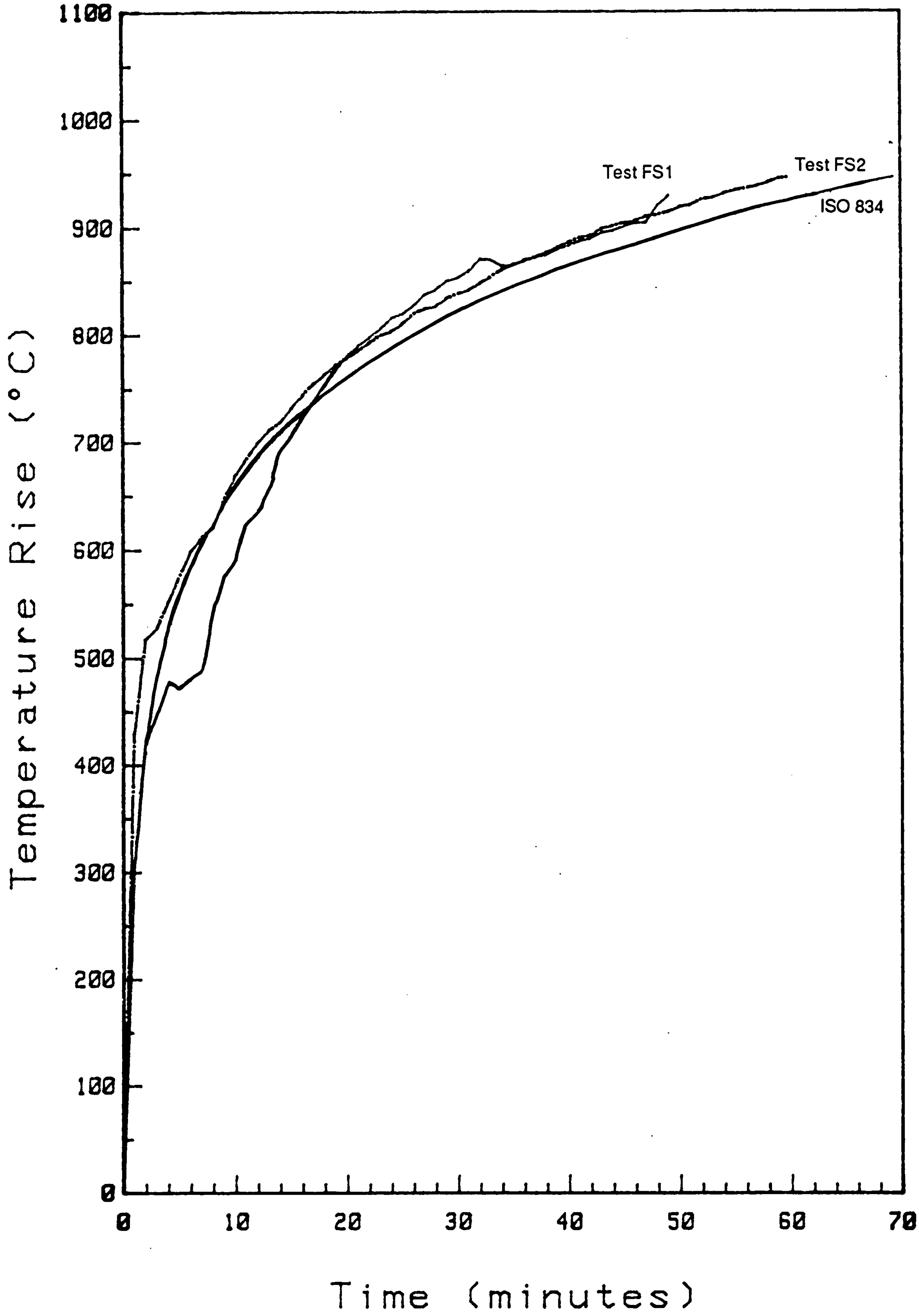


Figure 10: Comparison of average furnace and standard temperatures, tests FS1 & FS2.

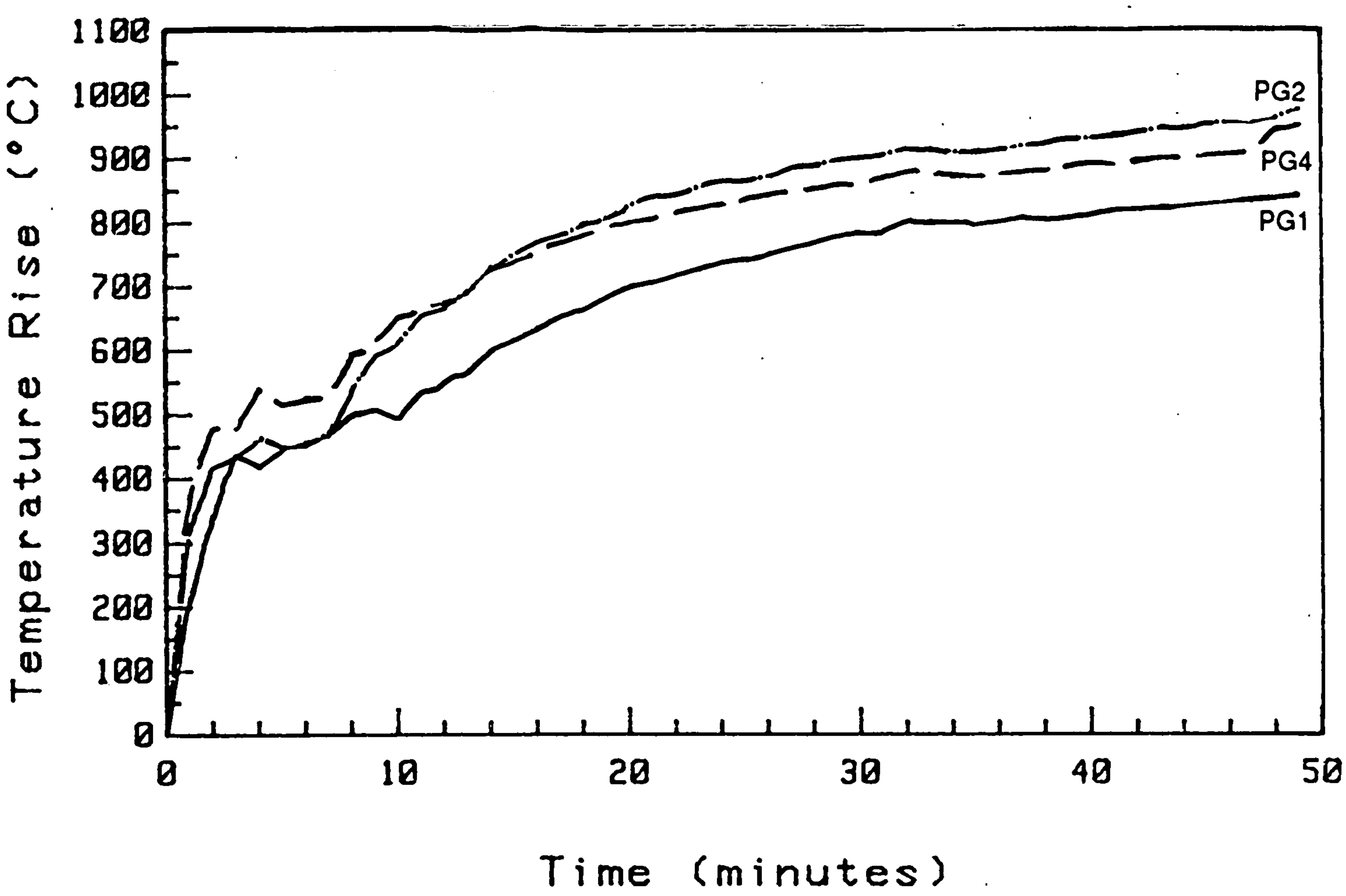


Figure 11a: Furnace temperatures100 mm below beams, test FS1.

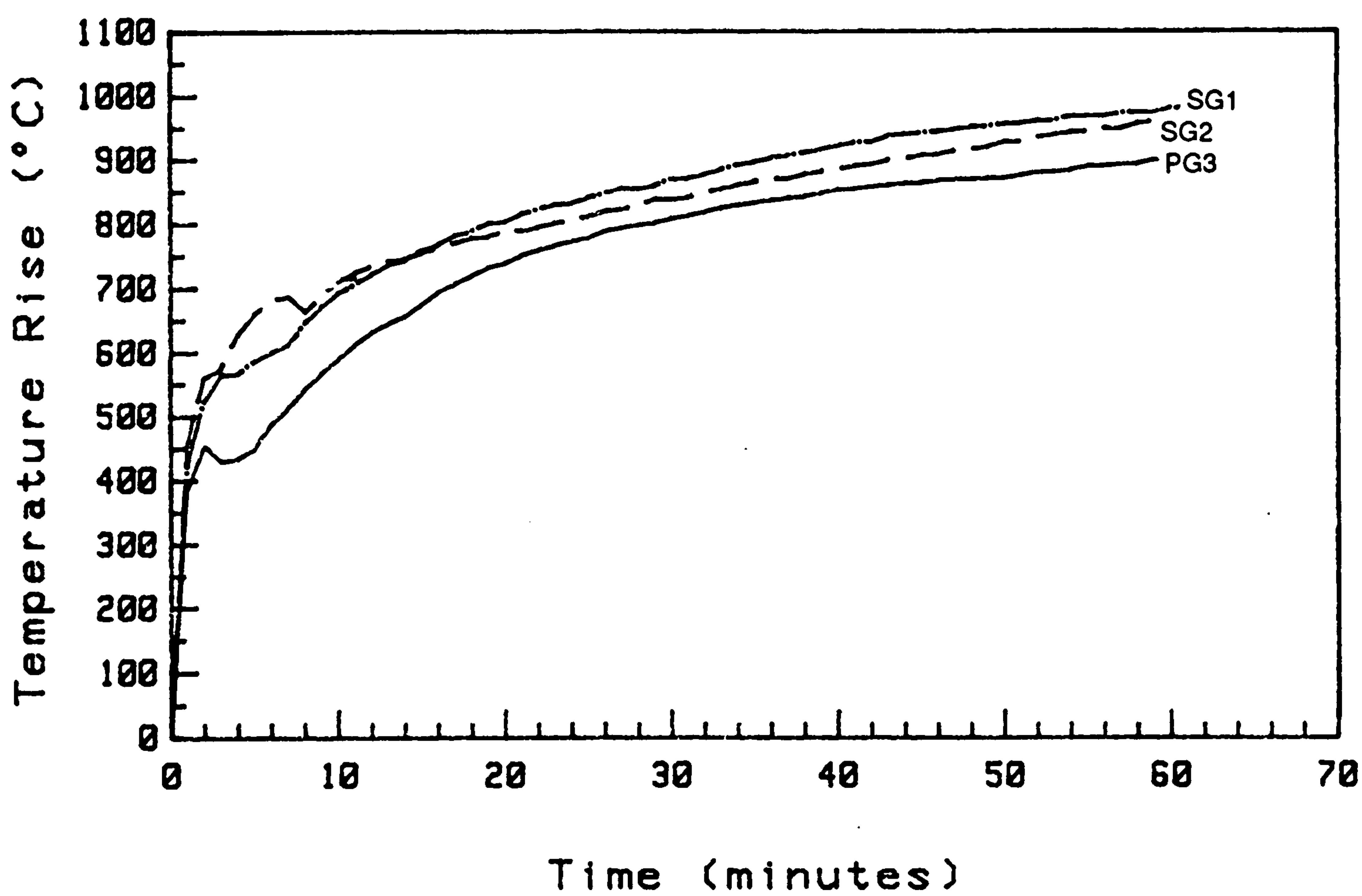


Figure 11b: Furnace temperatures 100 mm below beams, test FS2.

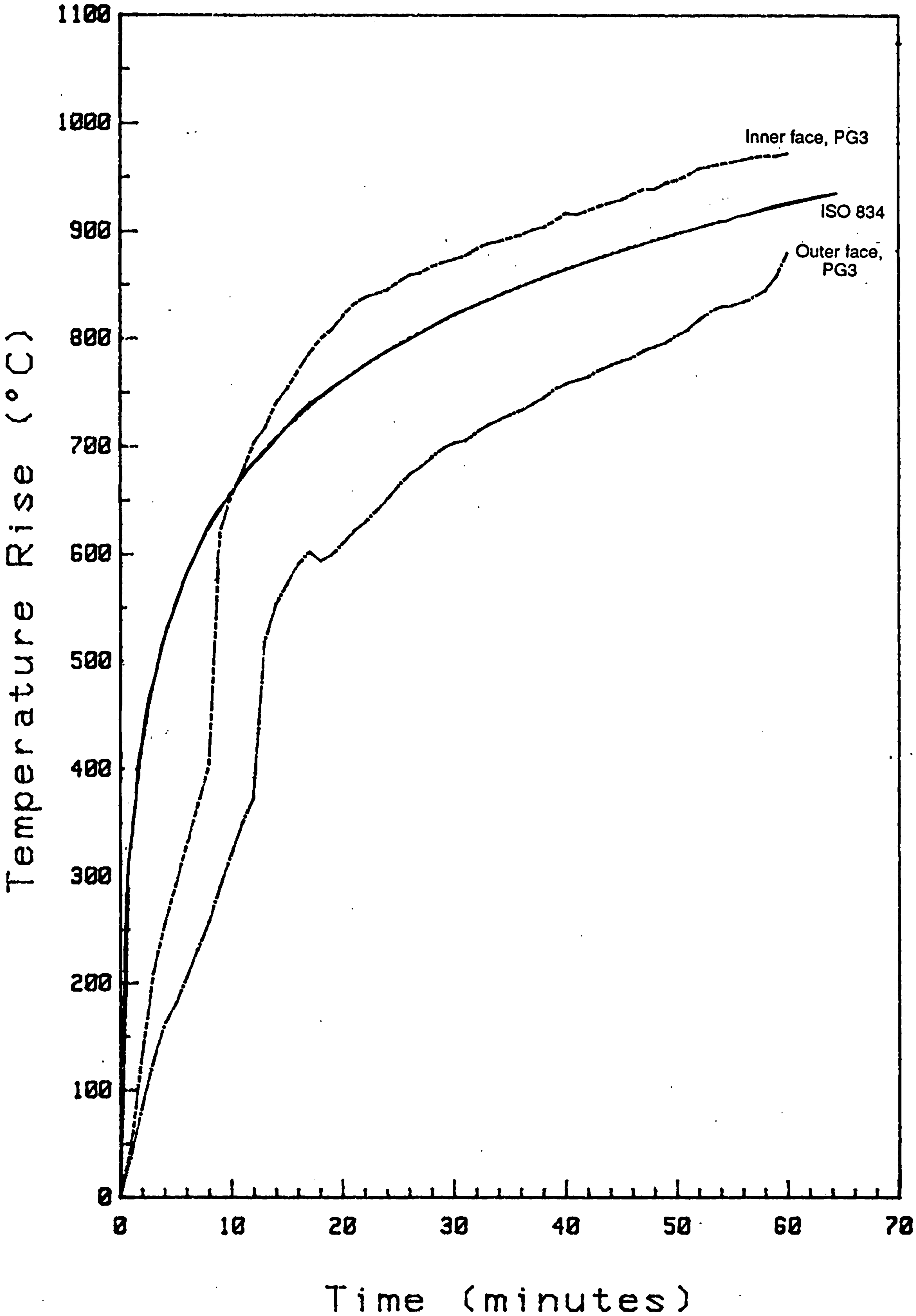


Figure 12: Furnace temperatures of joint PG3.

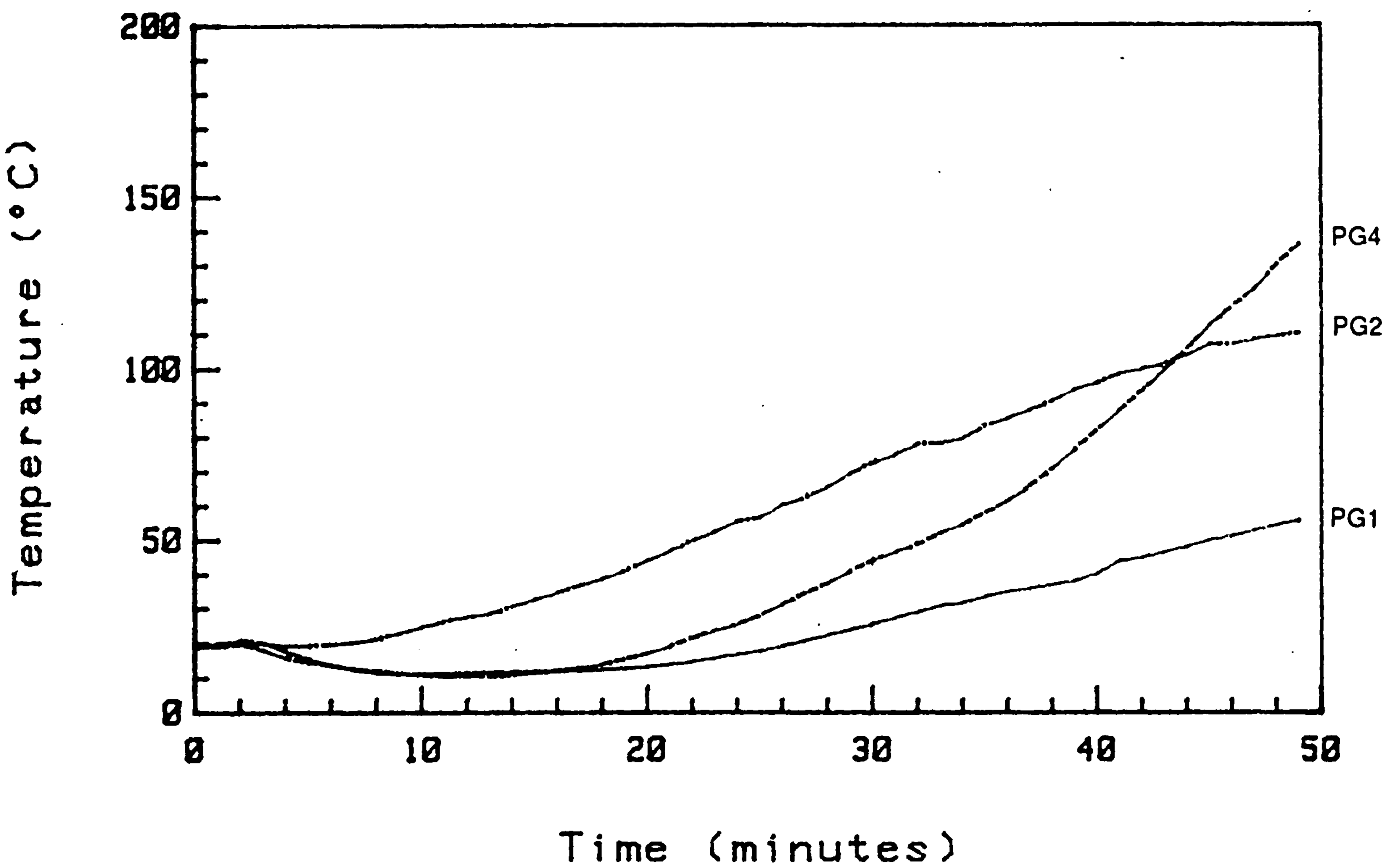


Figure 13a: Temperatures on beam surface beneath gussets, test FS1.

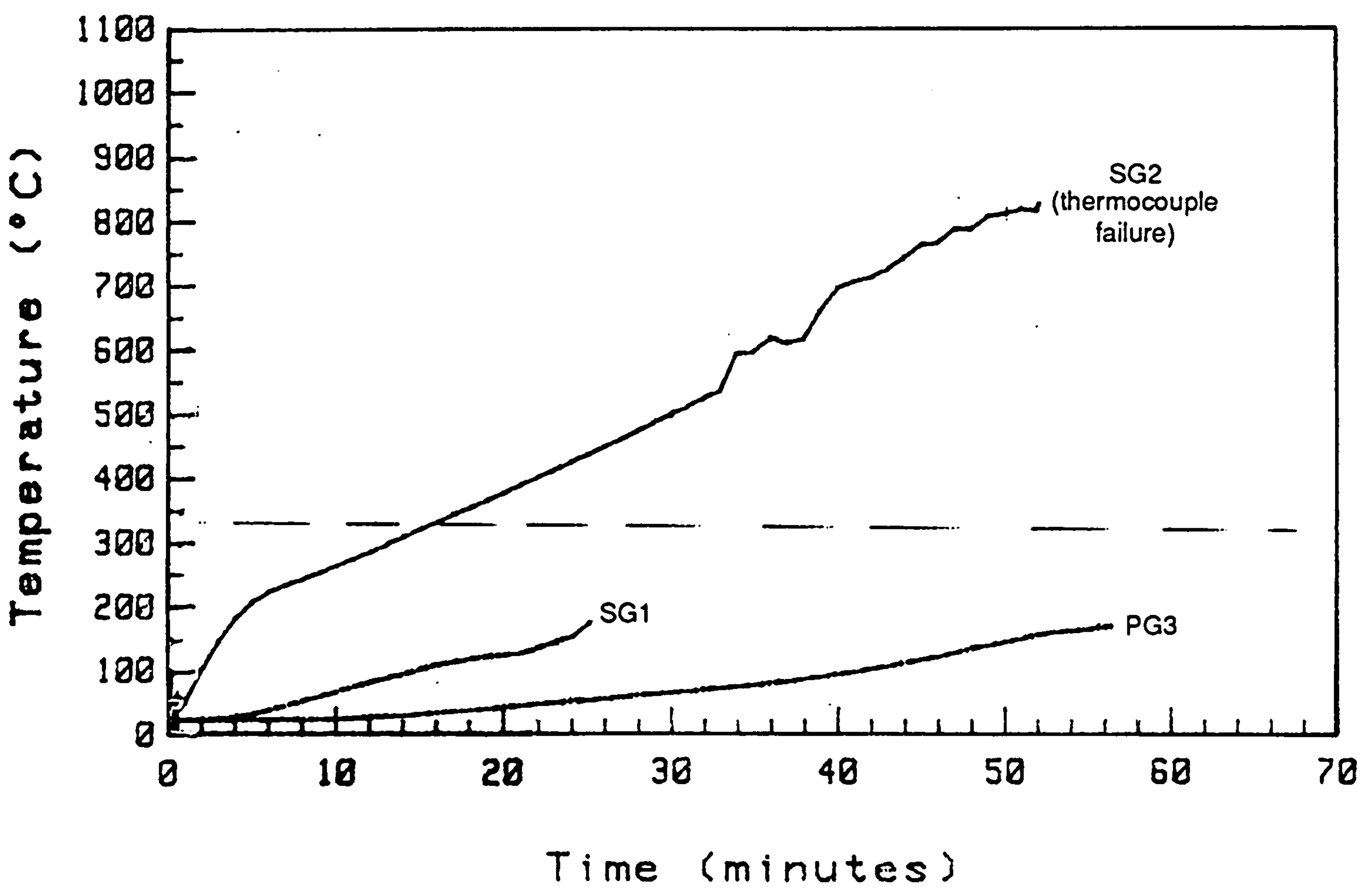


Figure 13b: Temperatures on beam surface beneath gussets, test FS2.

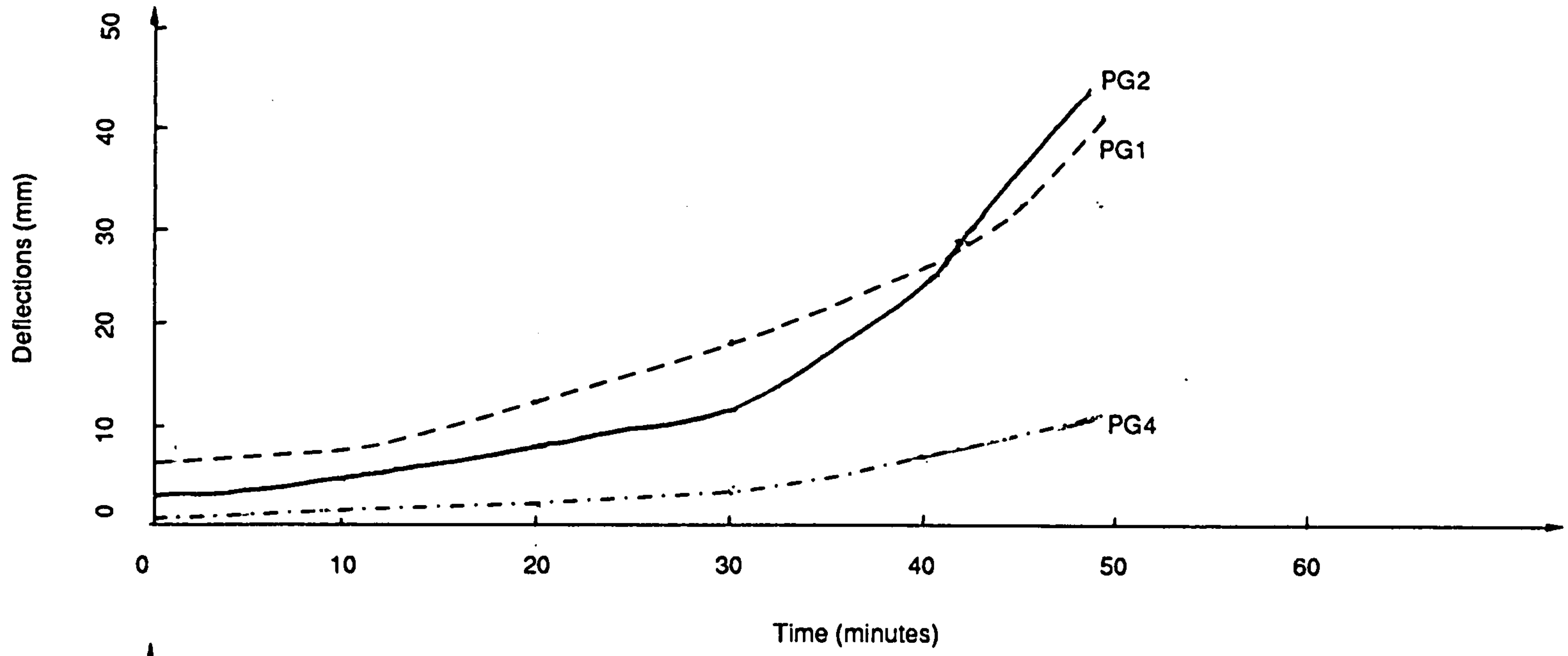


Figure 14a : Midspan Deflections Test FS1

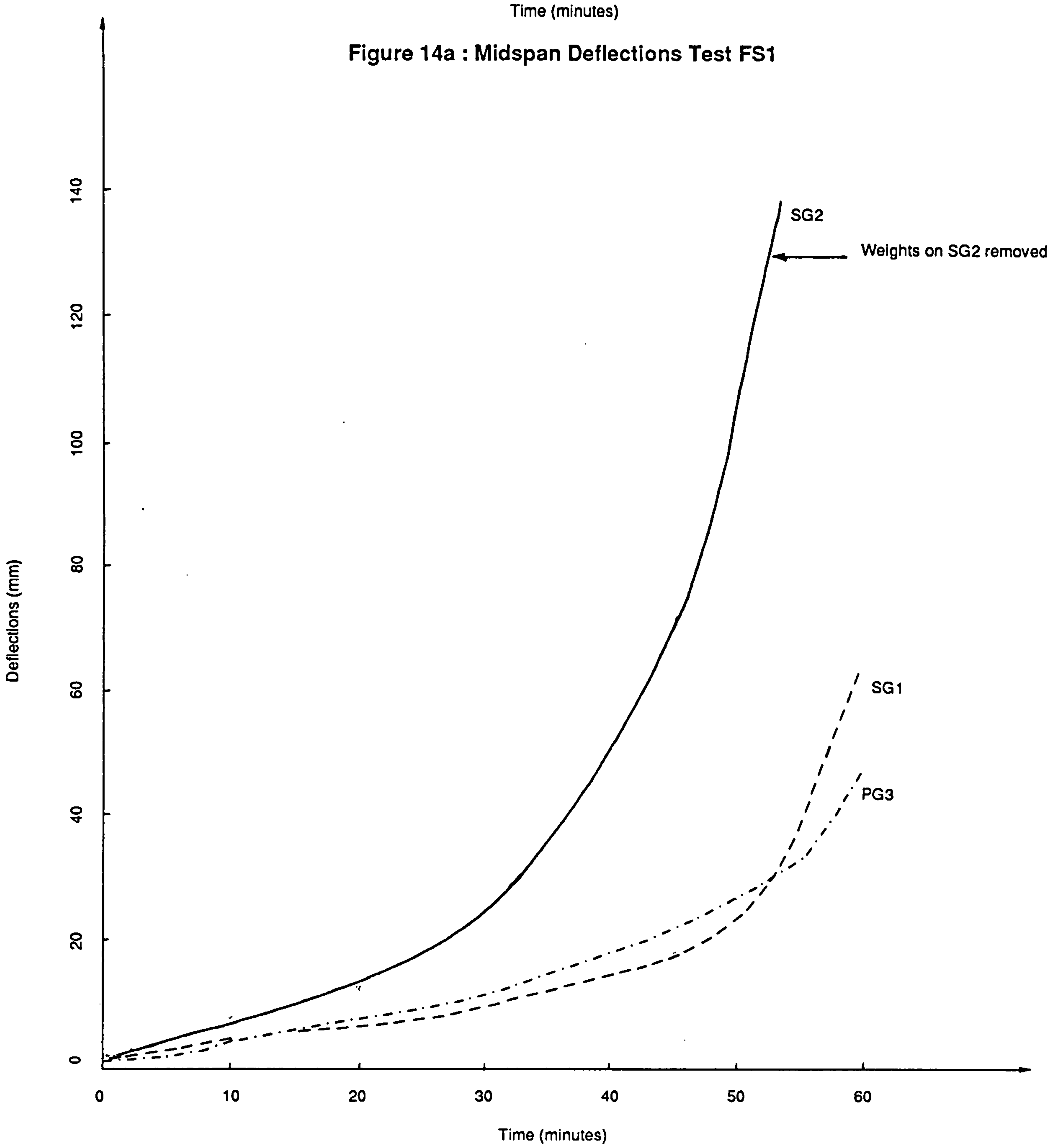
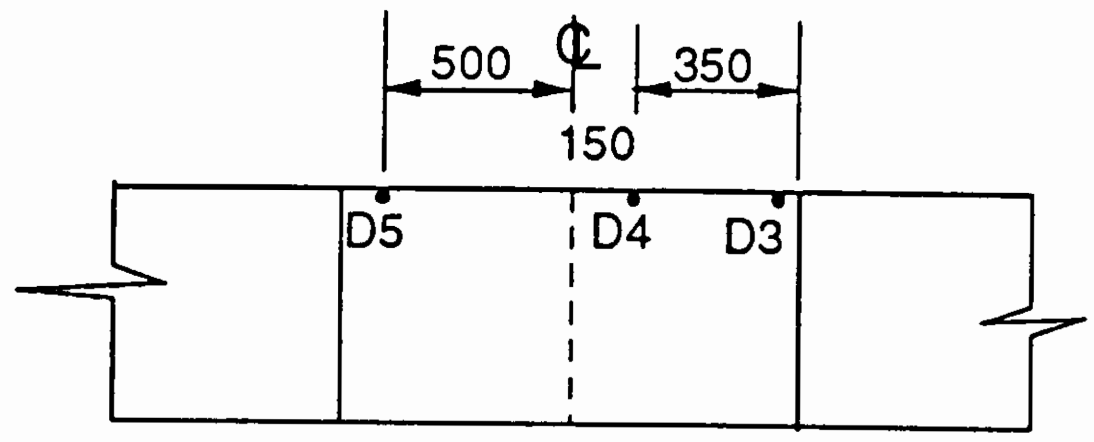


Figure 14b : Midspan Deflections Test FS2



Unloaded Joint

$$\vartheta = \frac{D4 - D3 + 0.35\,(D5 - D3)}{350} = \frac{D4 + 0.35\,D5 - 1.35\,D3}{350}$$

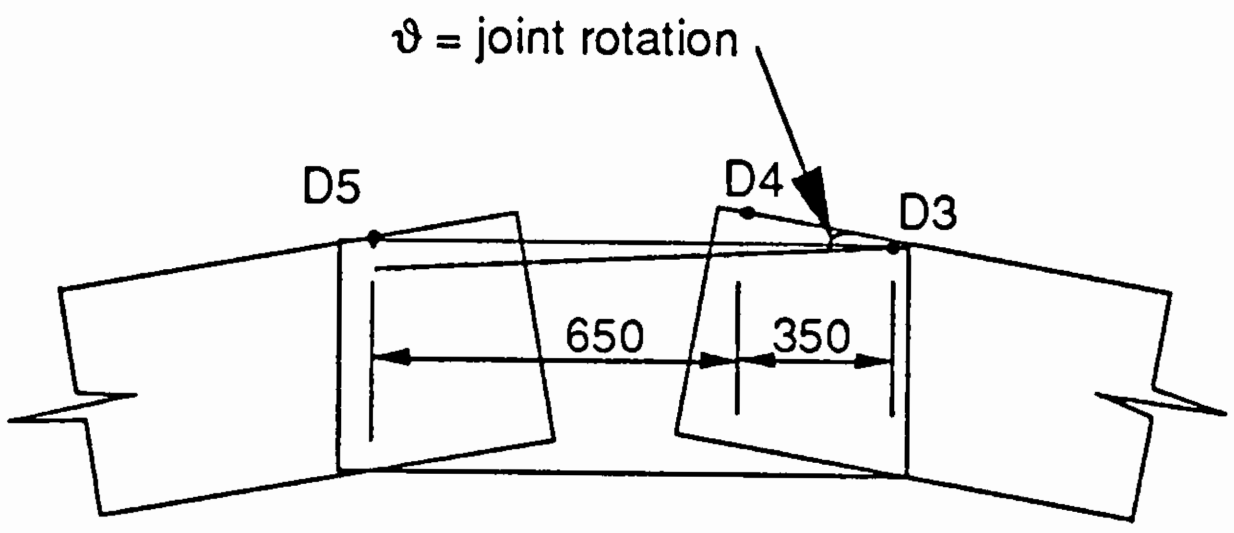


Figure 15a : Deformed Joint (exaggerated deformation) D3, D4, D5, are deflection measurement point

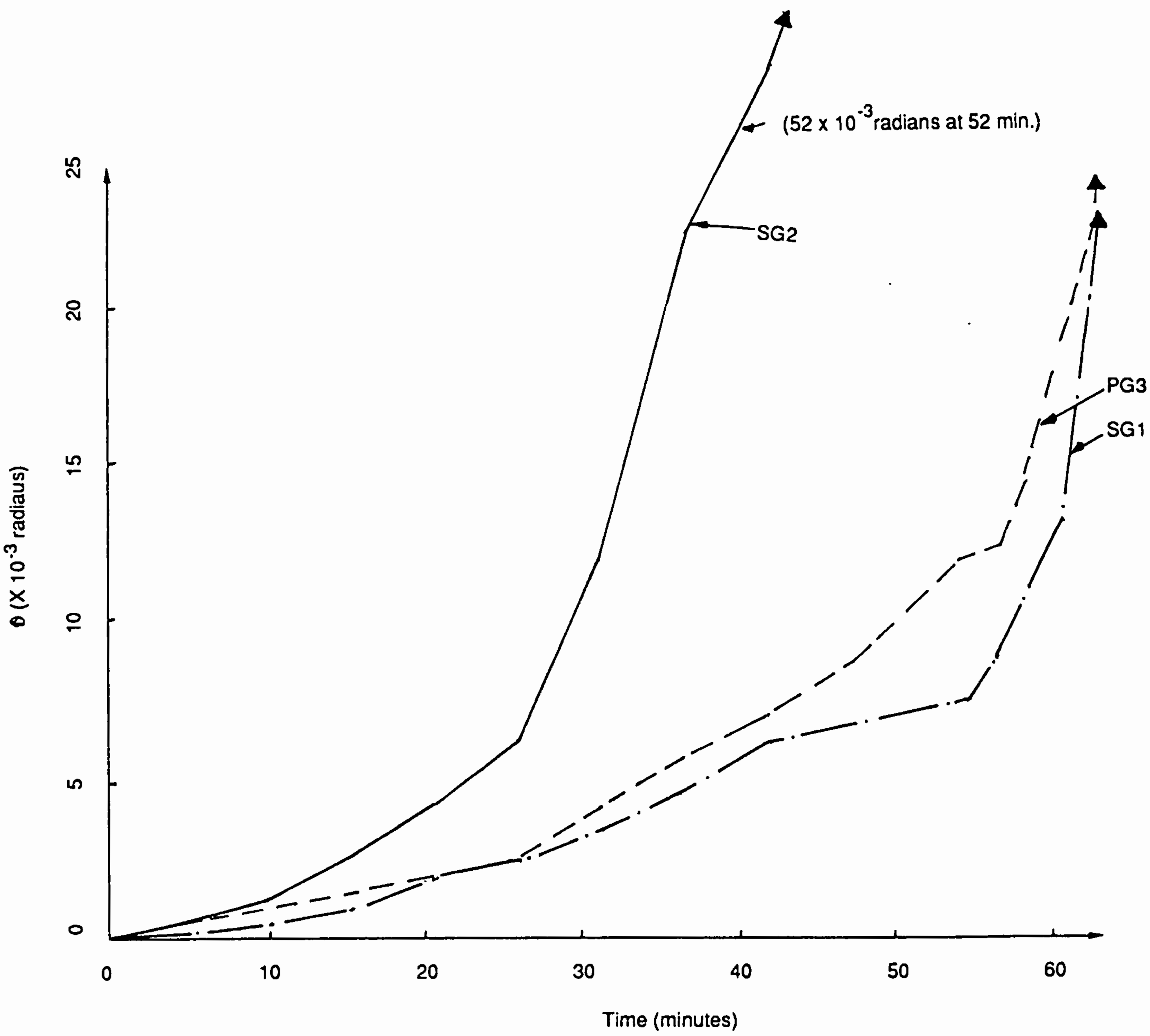


Figure 15b : Joint Rotations of Test FS2

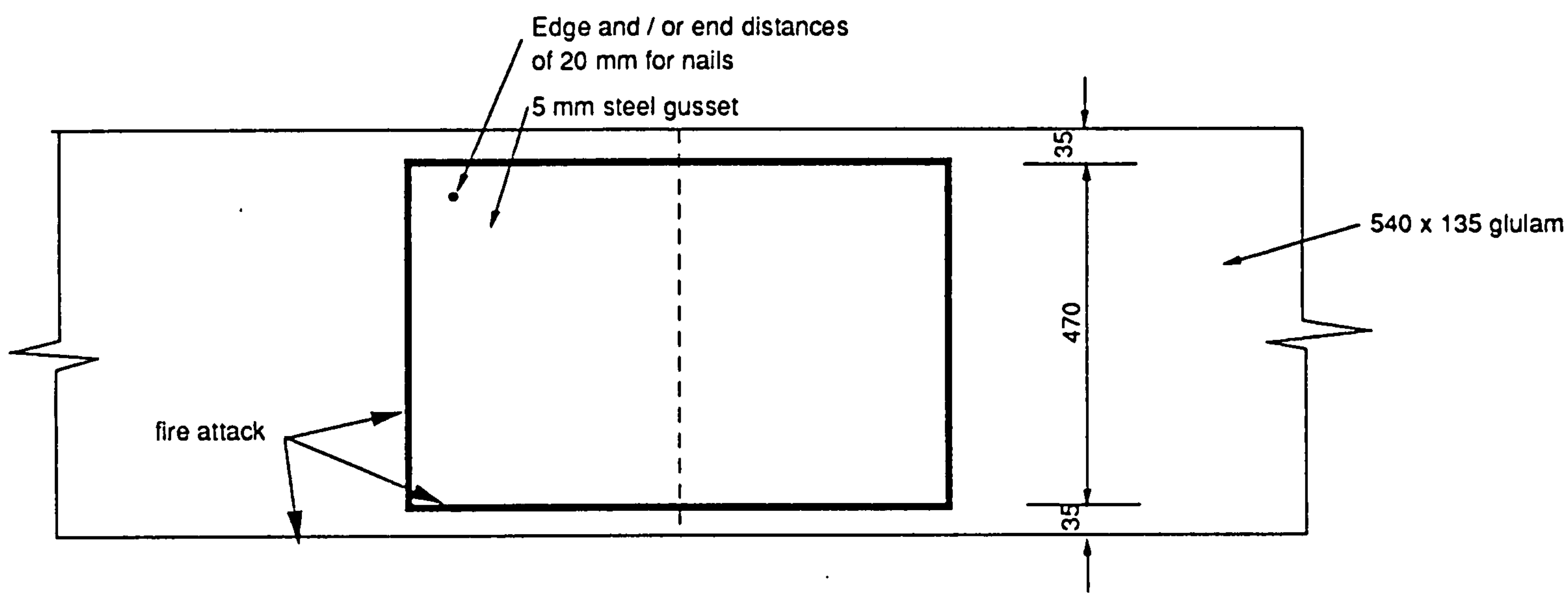


Figure 16a : Detail of joint SG2 Intumescent Coating Applied to Steel Gusset

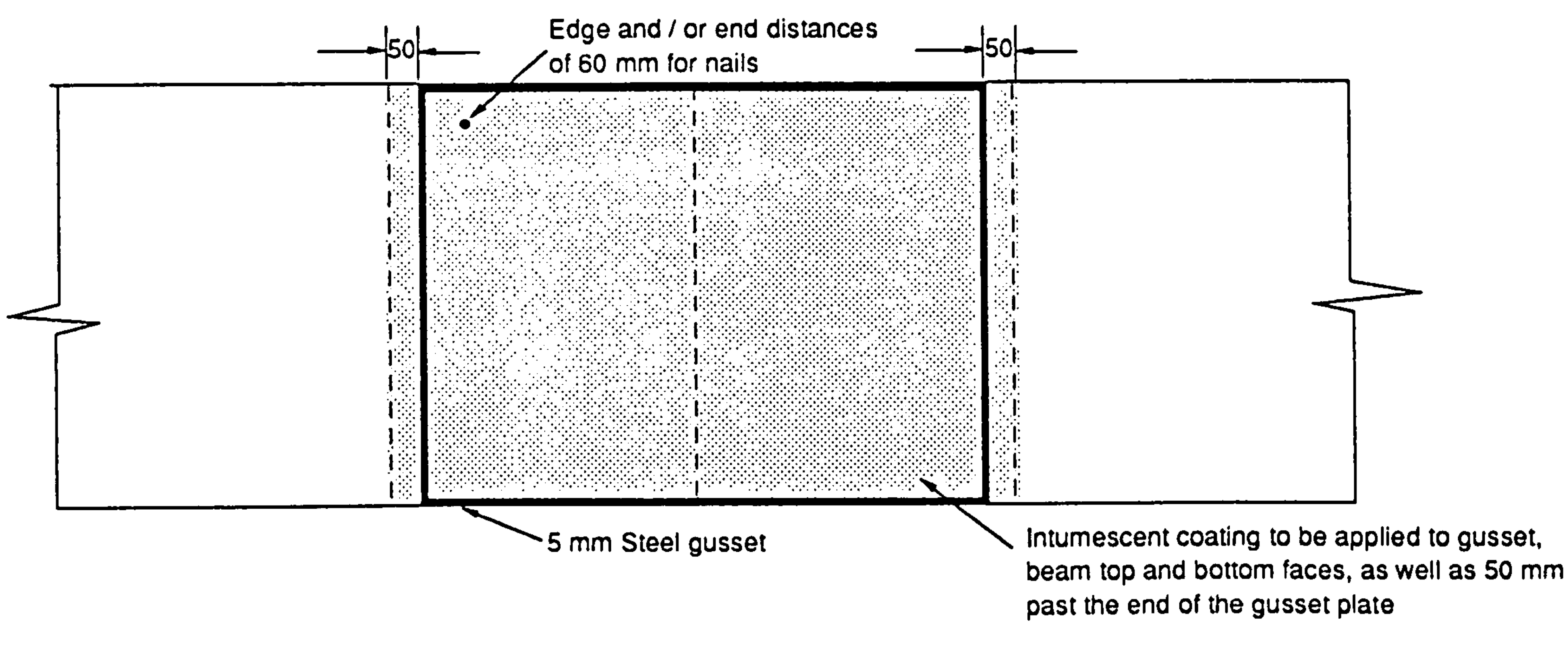


Figure 16b : Suggested detailing of gusset with Intumescent coating

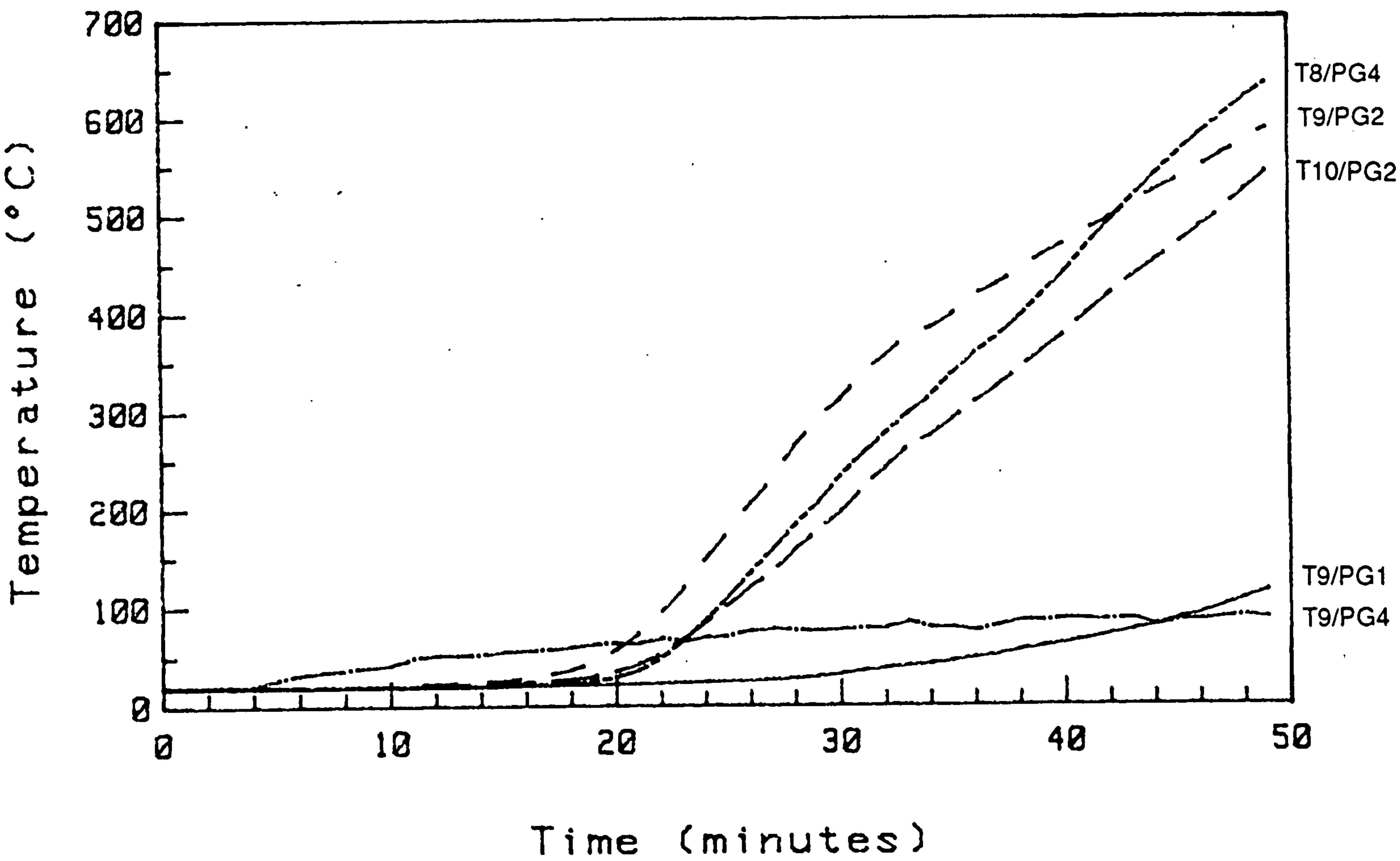


Figure 17a: Temperatures 67 mm into beam - test FS1.

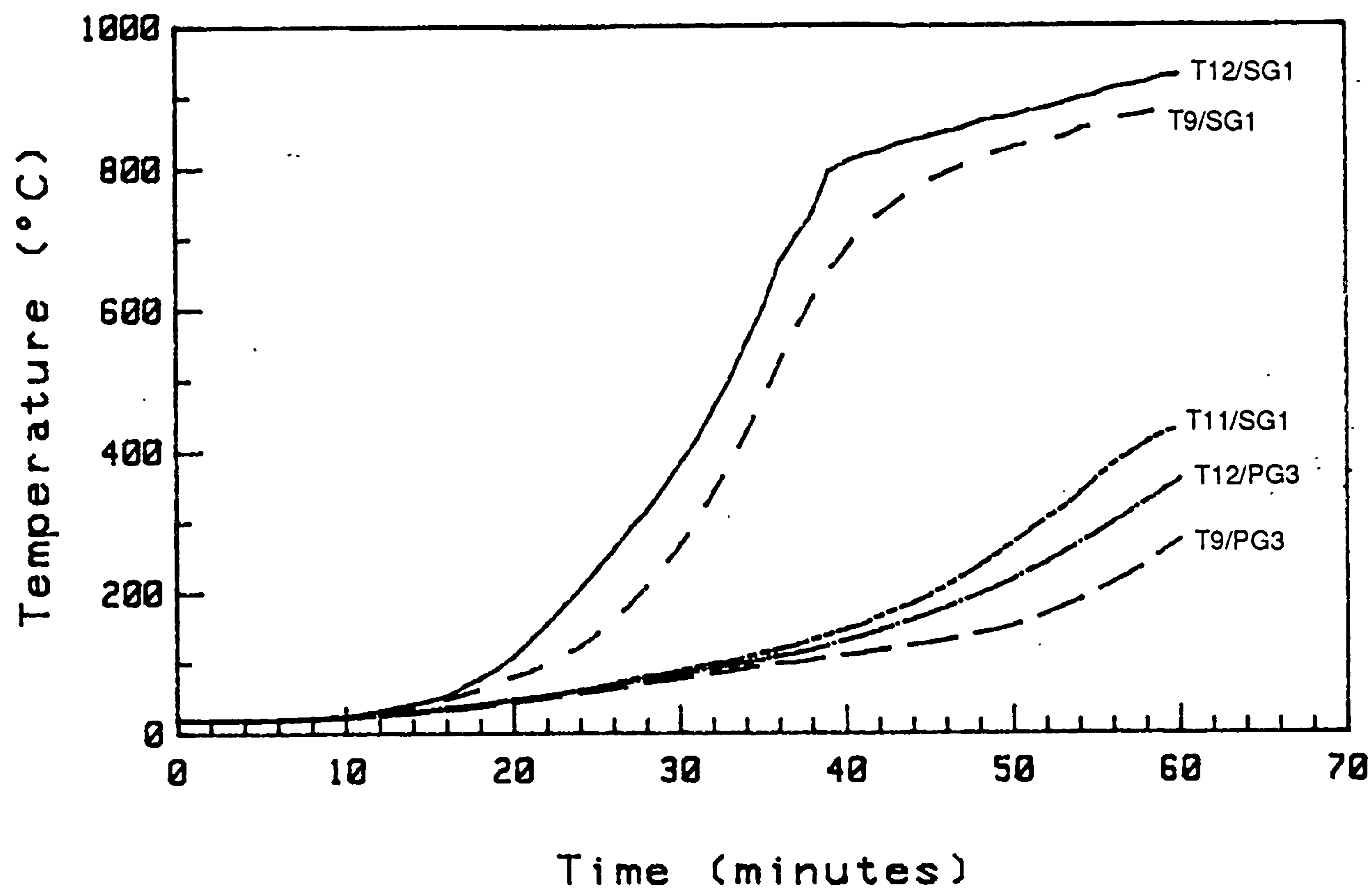


Figure 17b: Temperatures 45 mm into beam - test FS2.

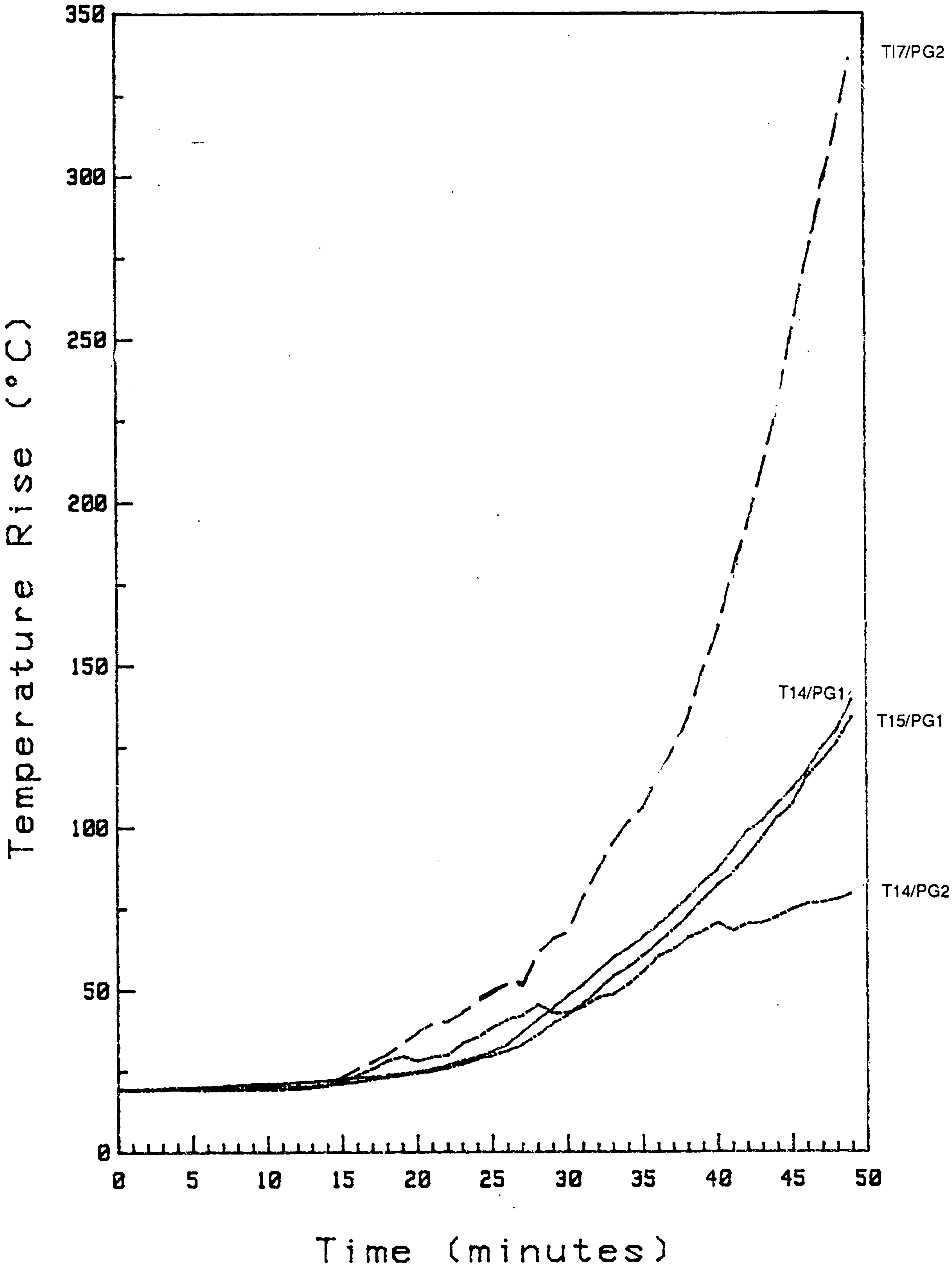


Figure 18: Nail tip temperatures.

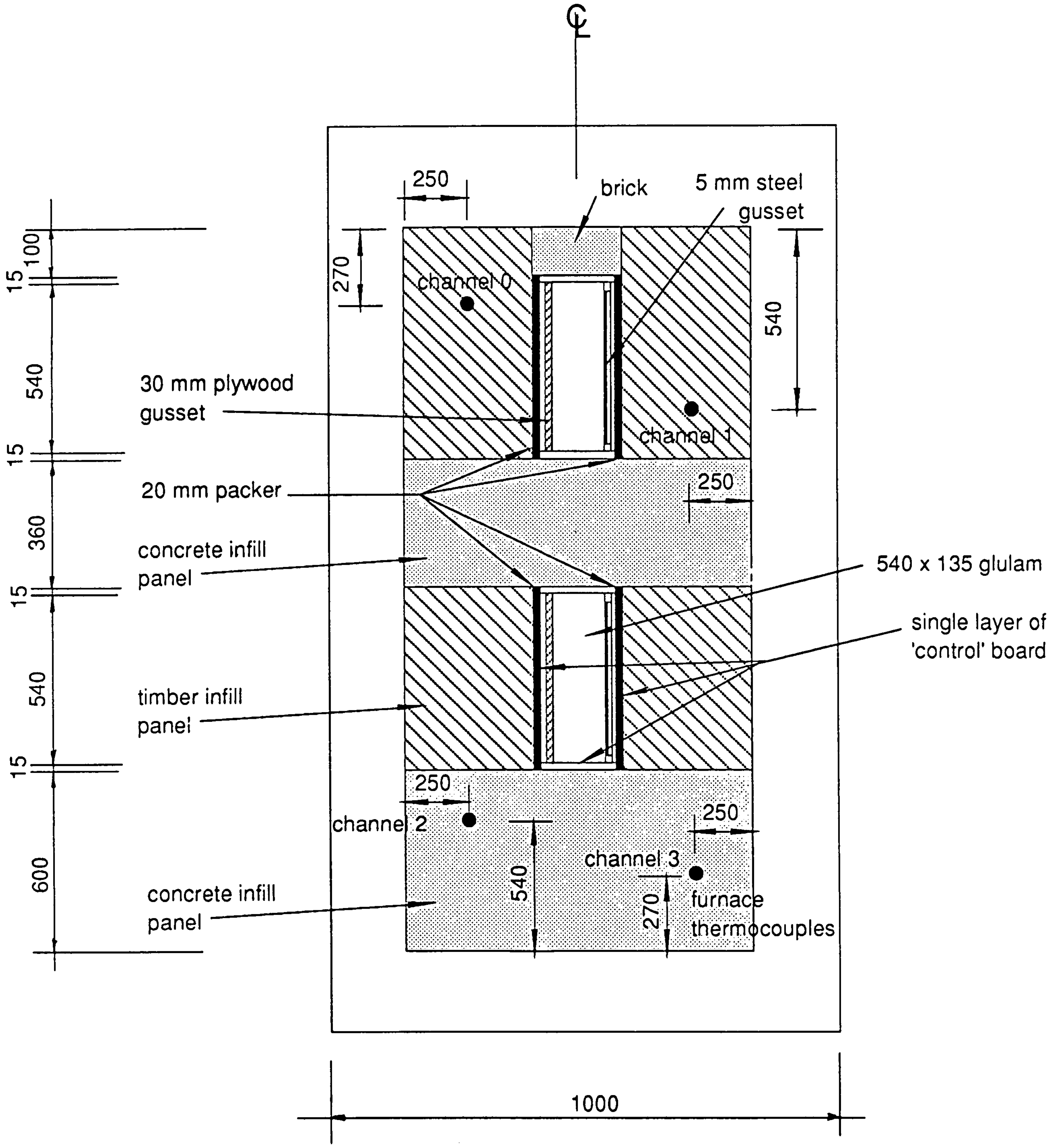
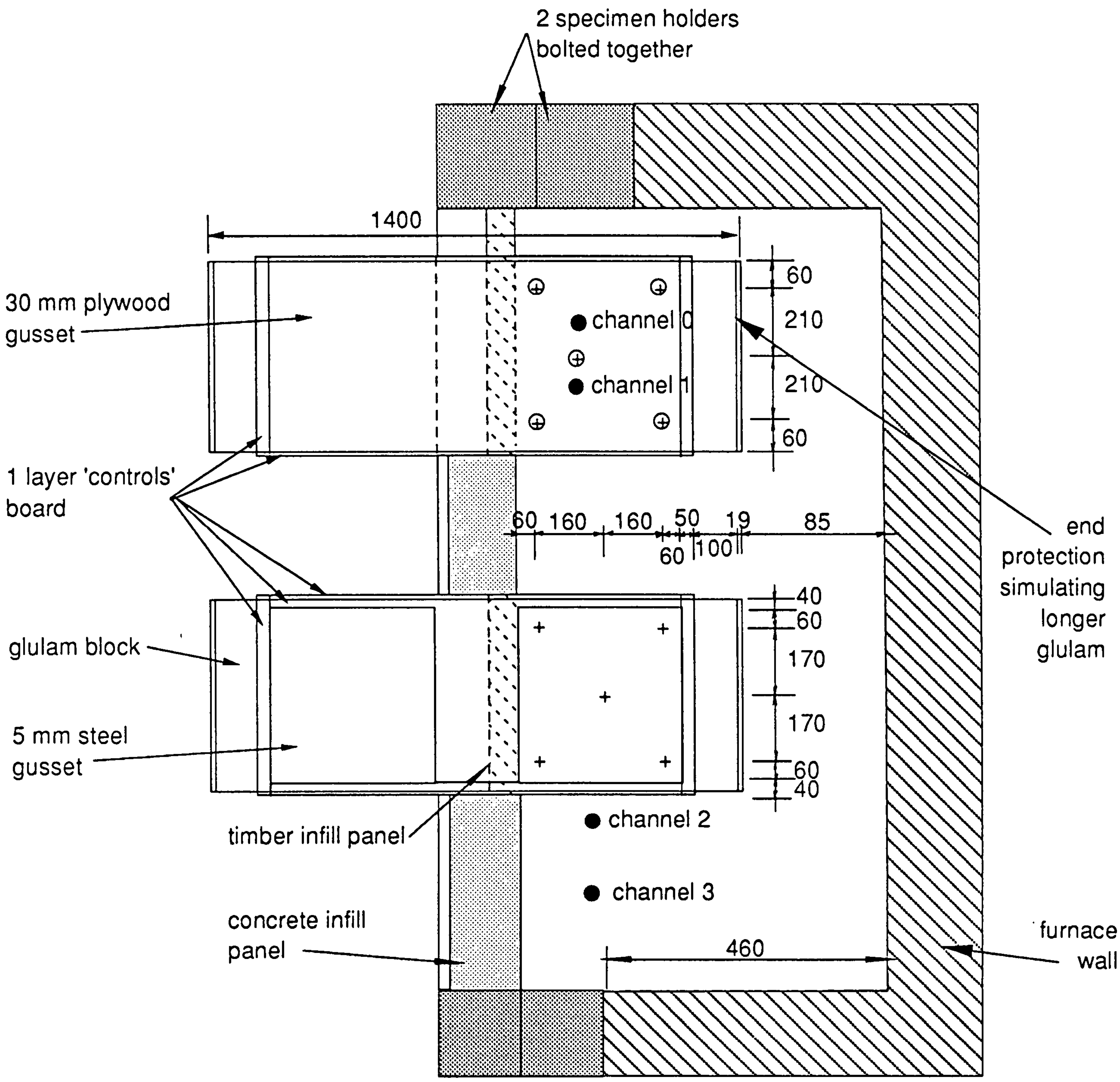


Figure 19 a : Elevation of Pilot Furnace Test P1. In Test P2, the Plywood Gussets Face the Other Wall.

10 mm air gap between steel gusset and a single layer of 'control' board protection



○ sheath thermocouple between plywood gusset and ' control ' board

● furnace thermocouple

+ sheath thermocouple between glulam and gusset

Figure 19 b : Cross - Section Showing Details of Gusset

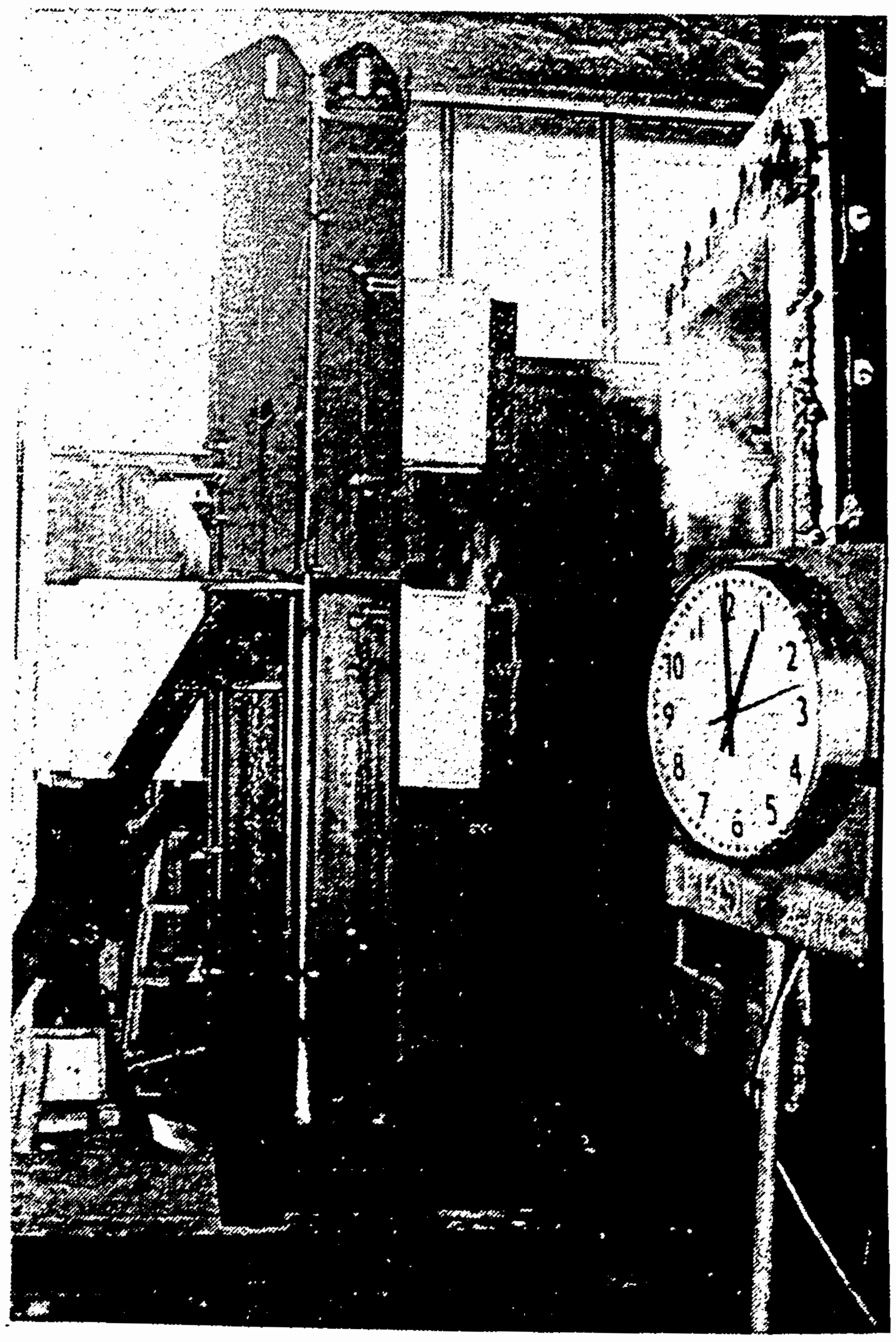


Figure 20a: View after test P1.

Figure 20b: View after test P2.

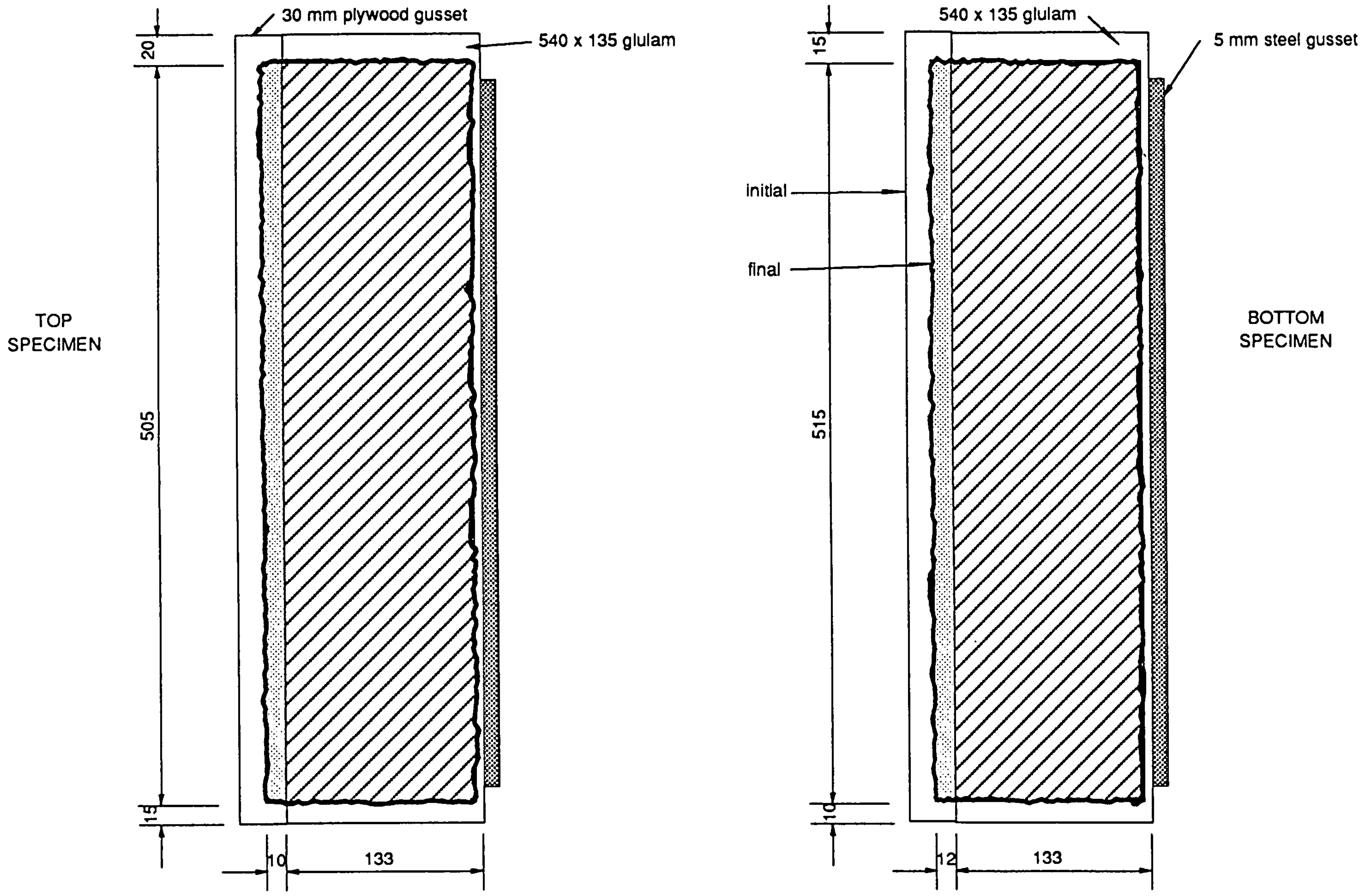


FIGURE 21a : Residual Sections of Test P1

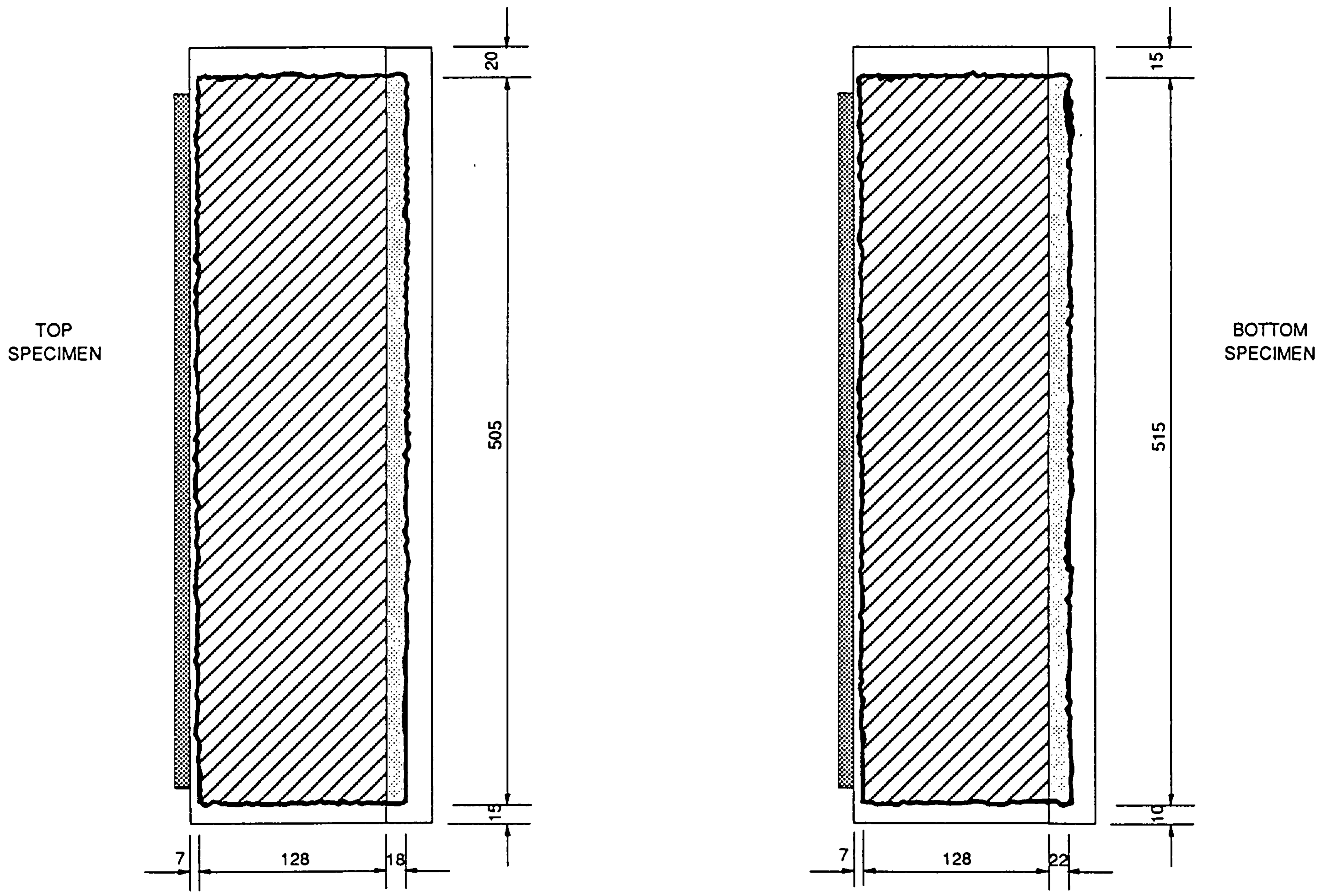


FIGURE 21b : Residual Sections of Test P2

Figure 22a: Glulam beneath steel gusset.

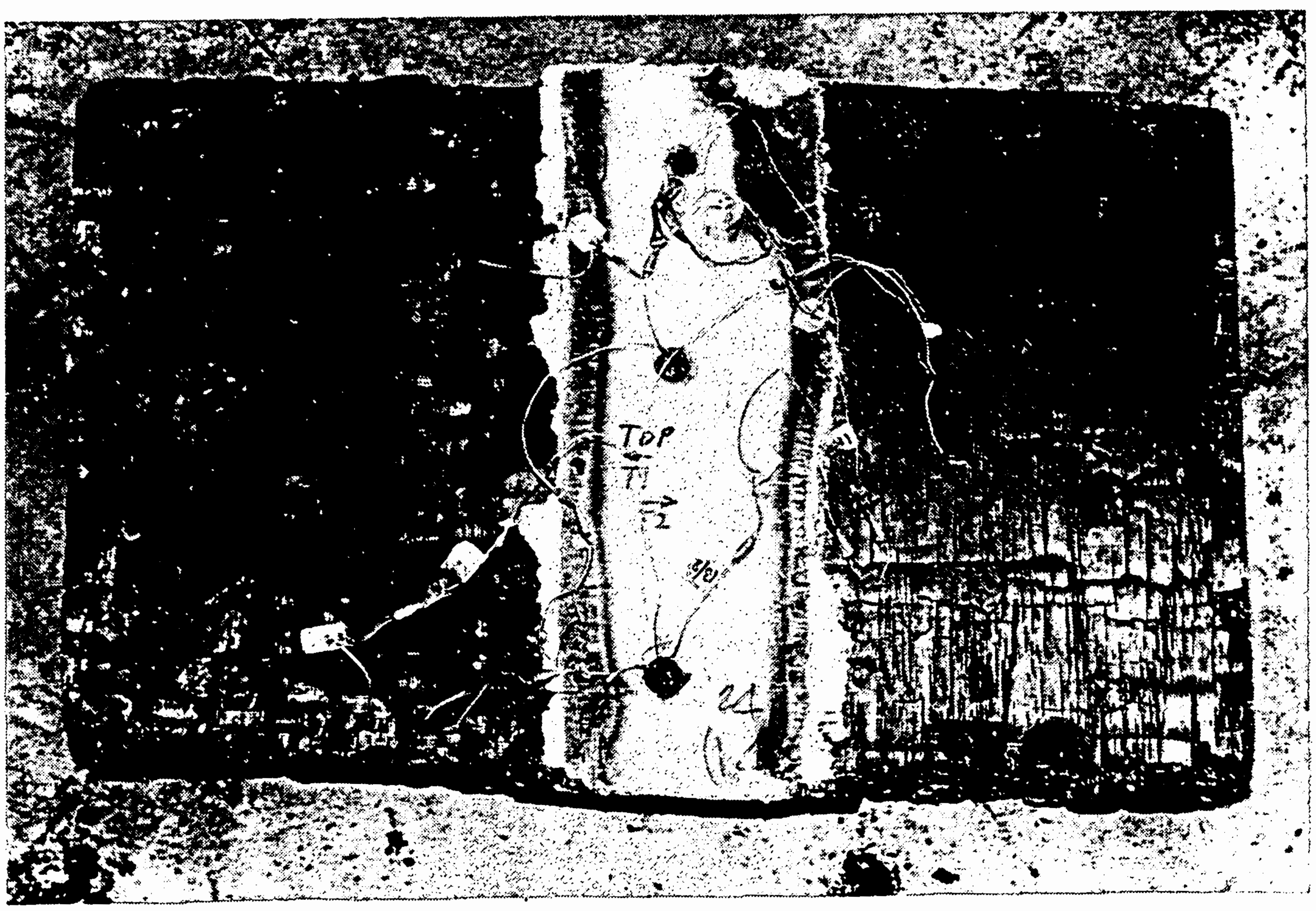


Figure 22b: Plywood gussets beneath 'control' board.

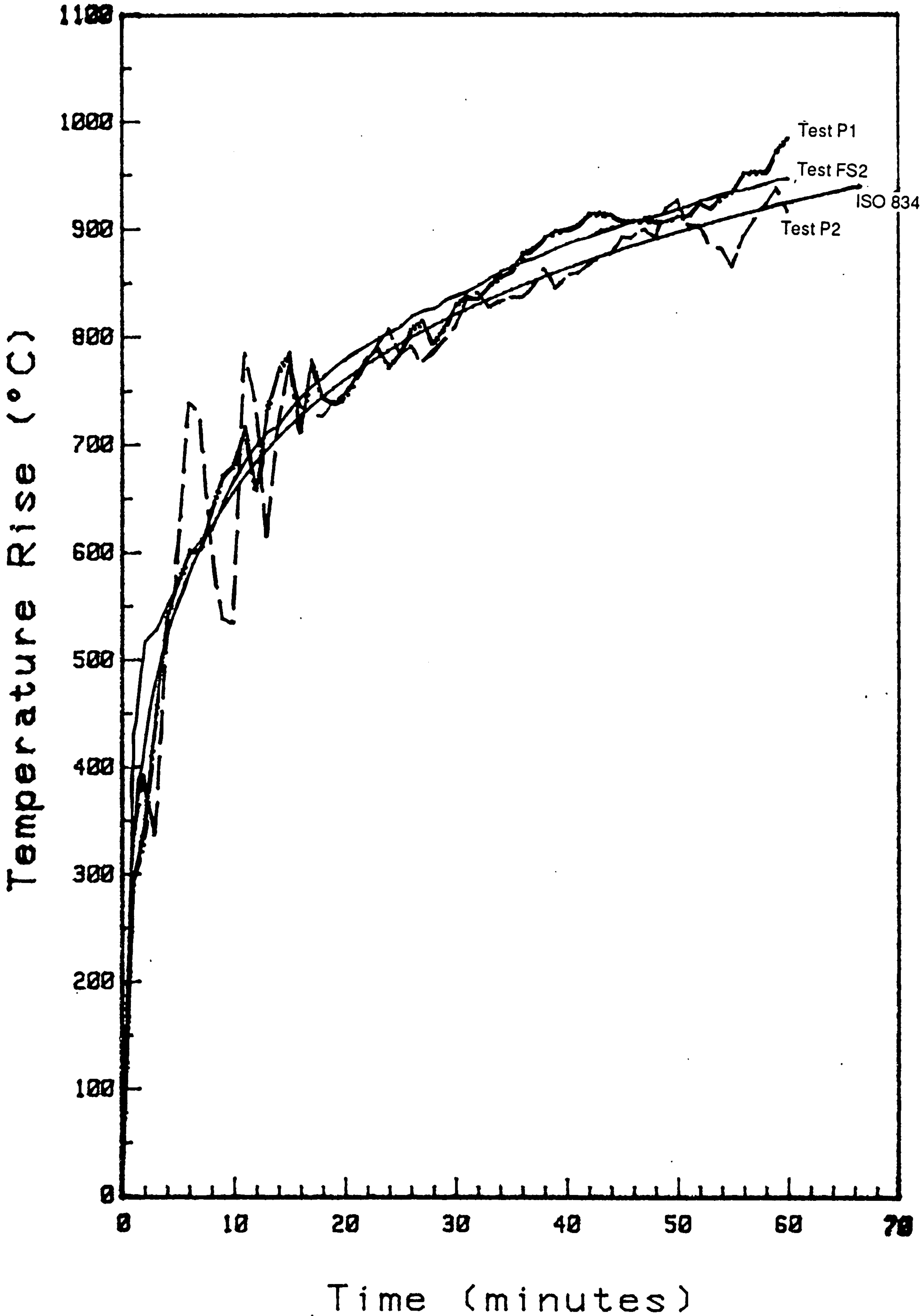


Figure 23: Comparison of average furnace and standard temperatures.

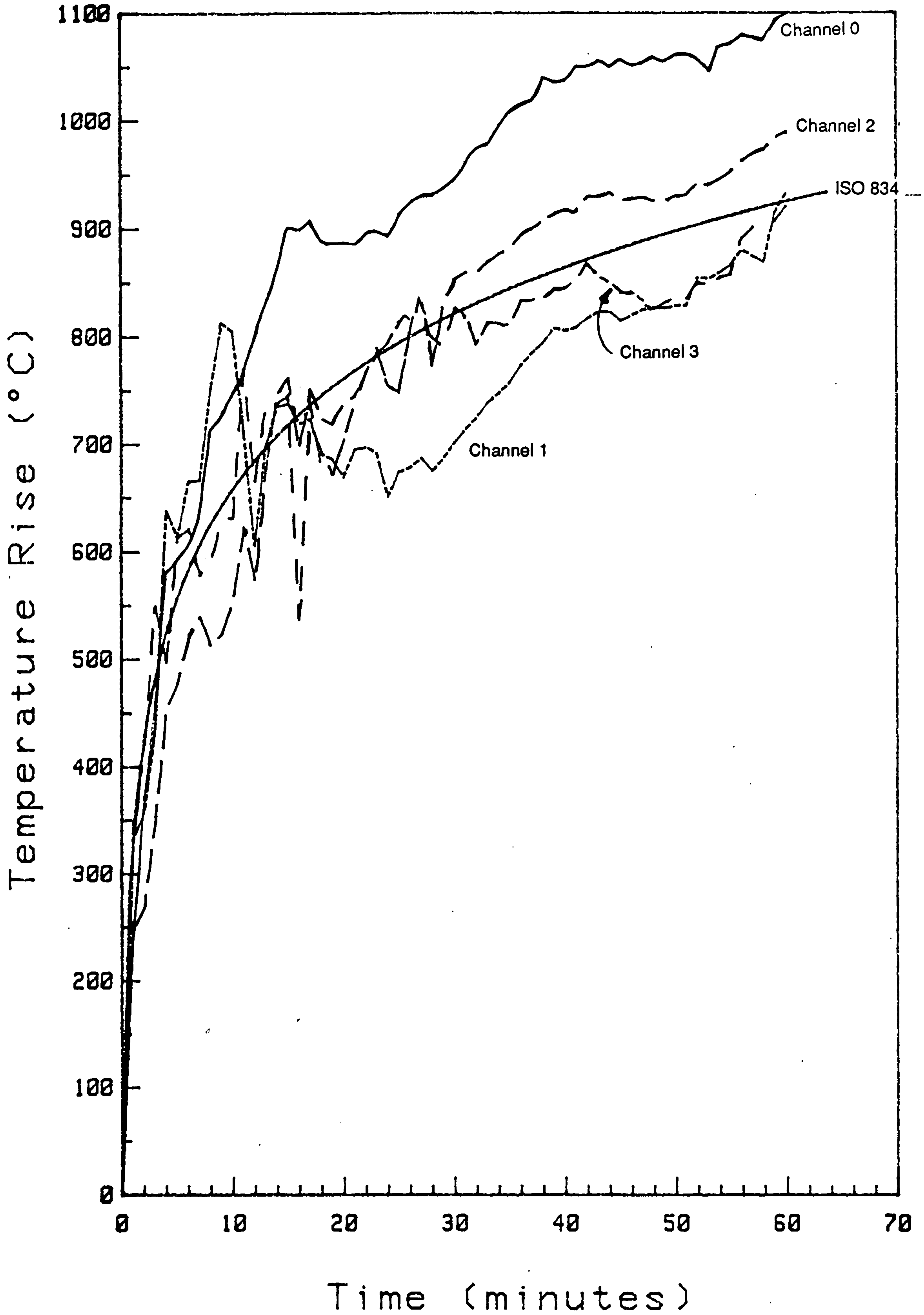


Figure 24a: Furnace temperatures - test P1.

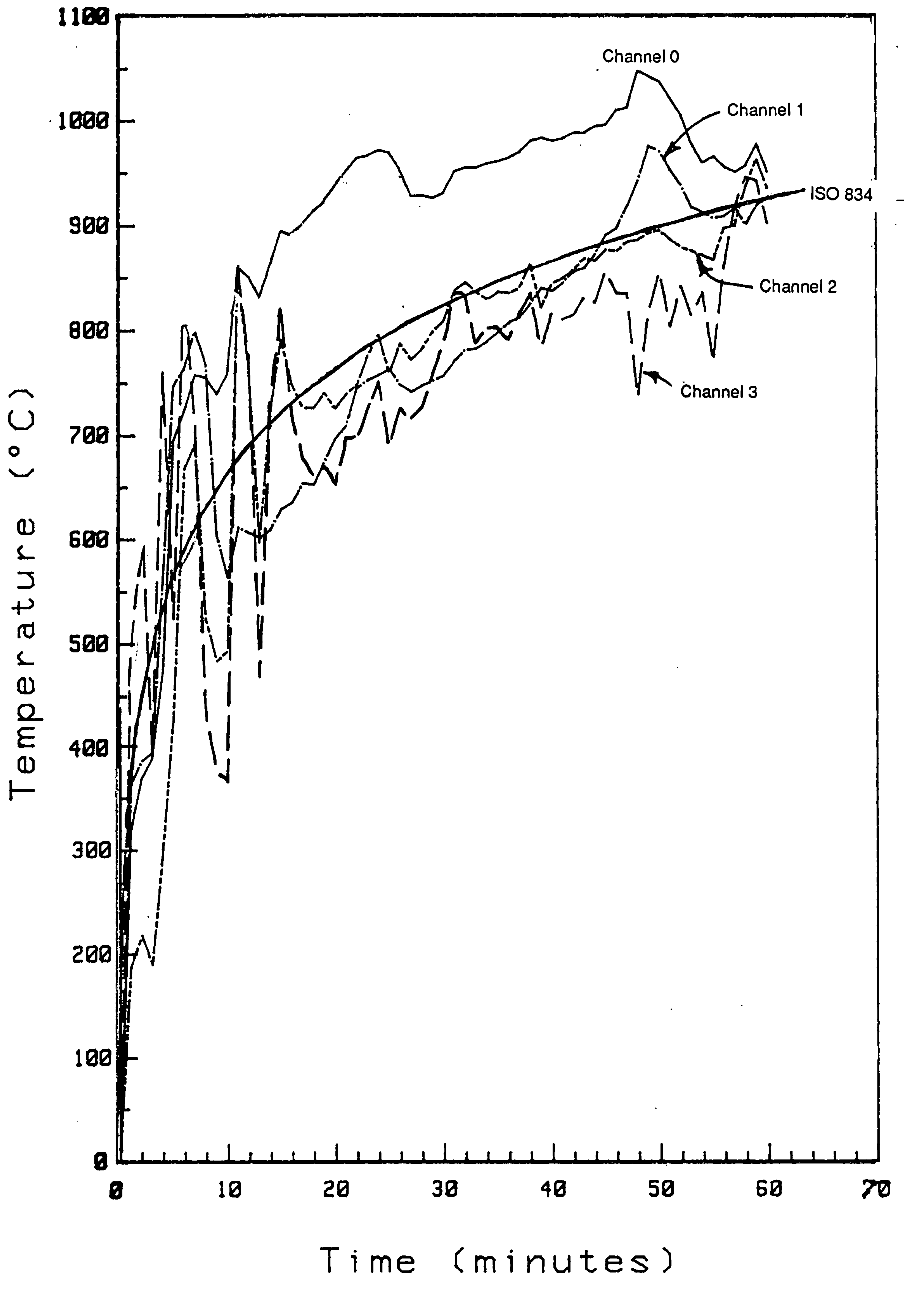


Figure 24b: Furnace temperatures - test P2.

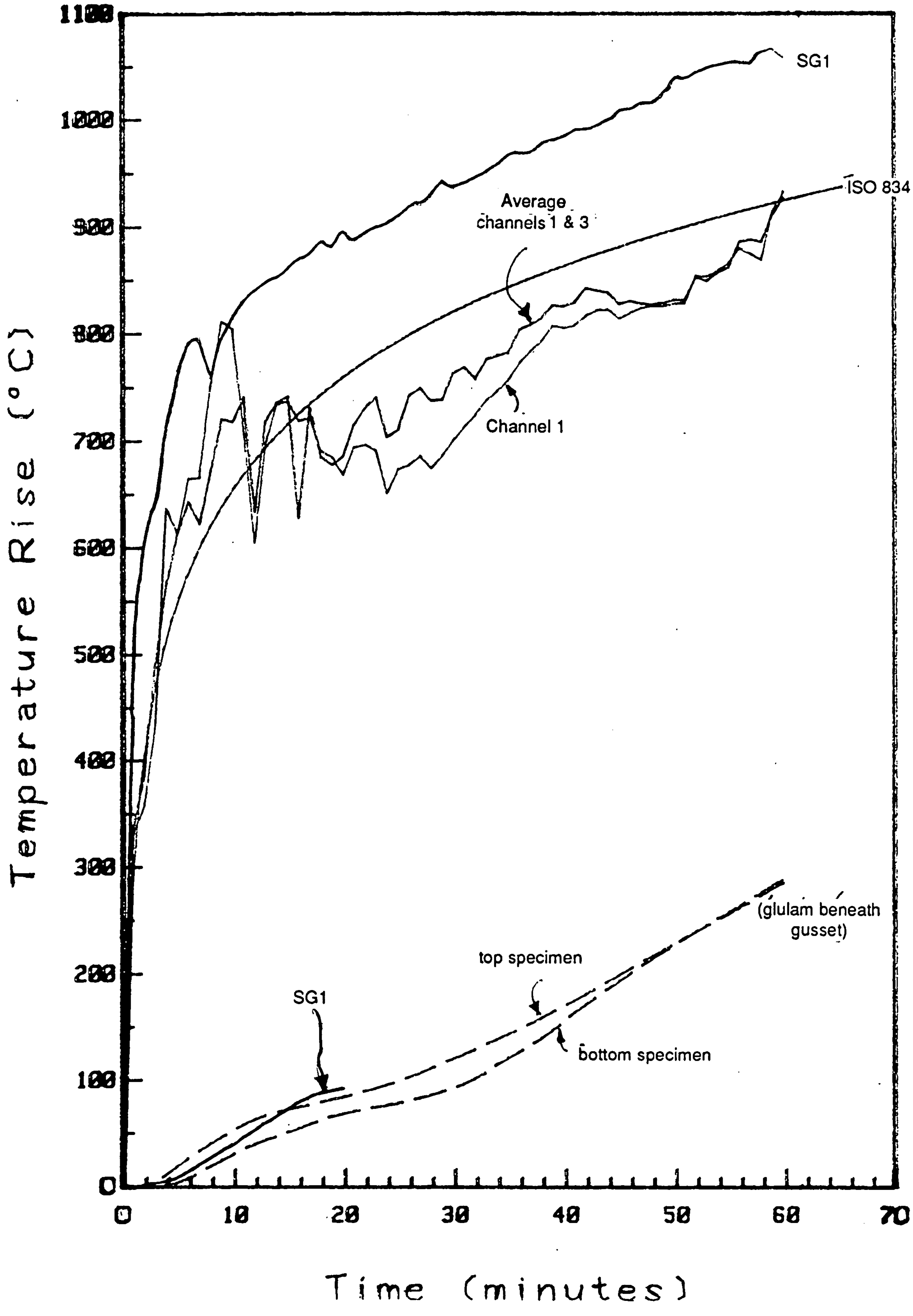


Figure 25a: Temperatures of steel specimens - test P1.

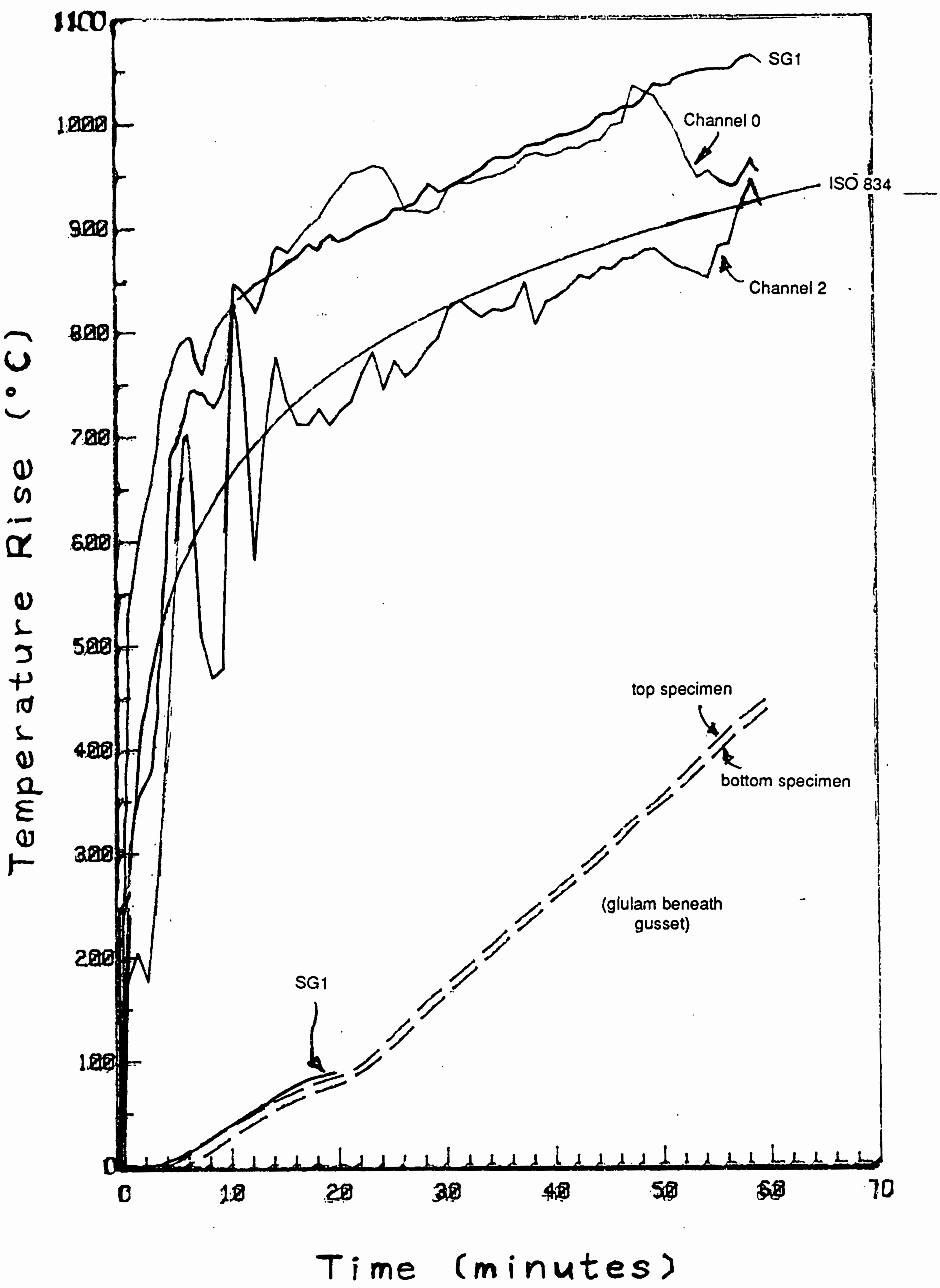


Figure 25b: Temperatures of steel specimens - Test P2.

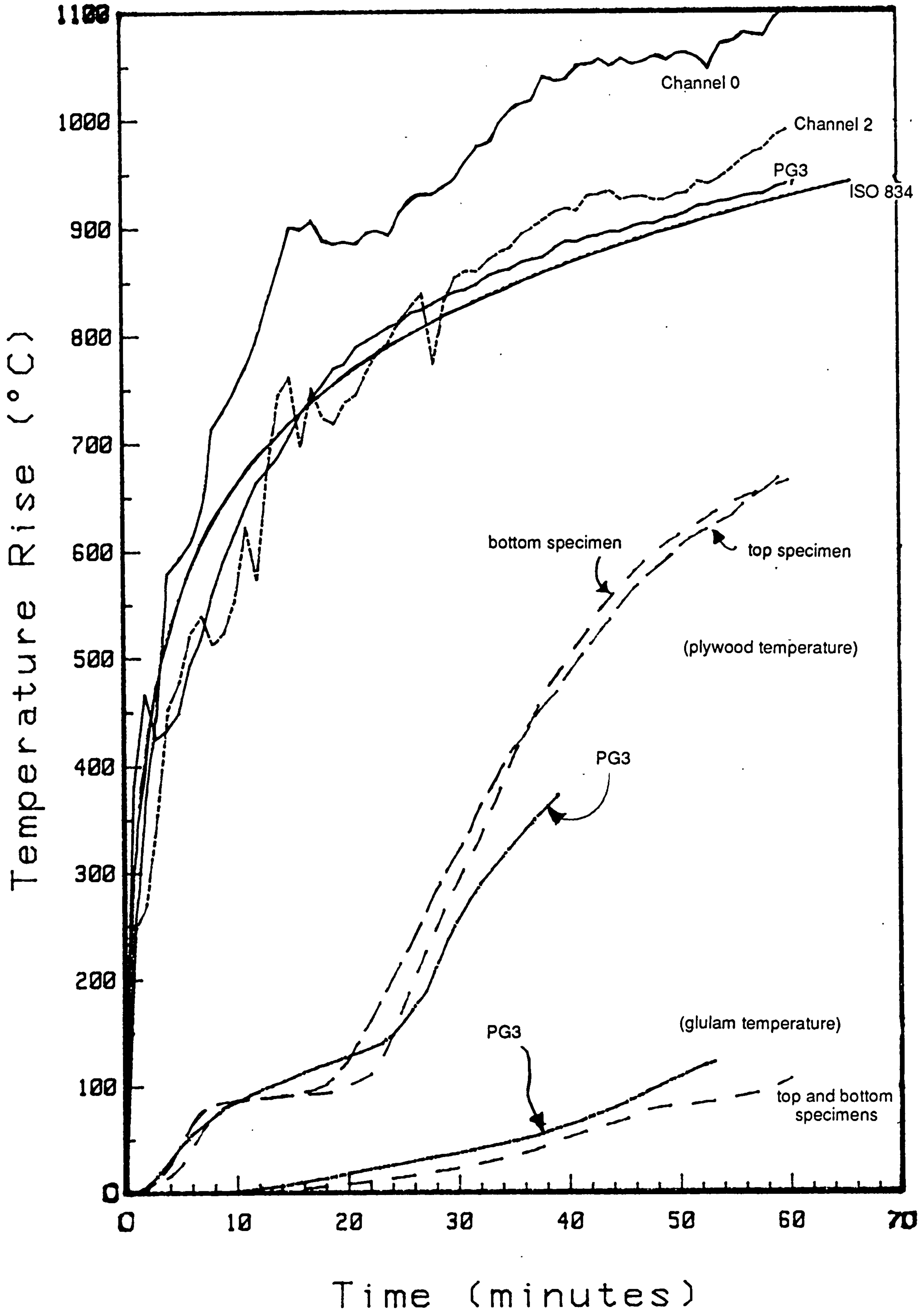


Figure 26a: Temperature of plywood specimens - Test P1.

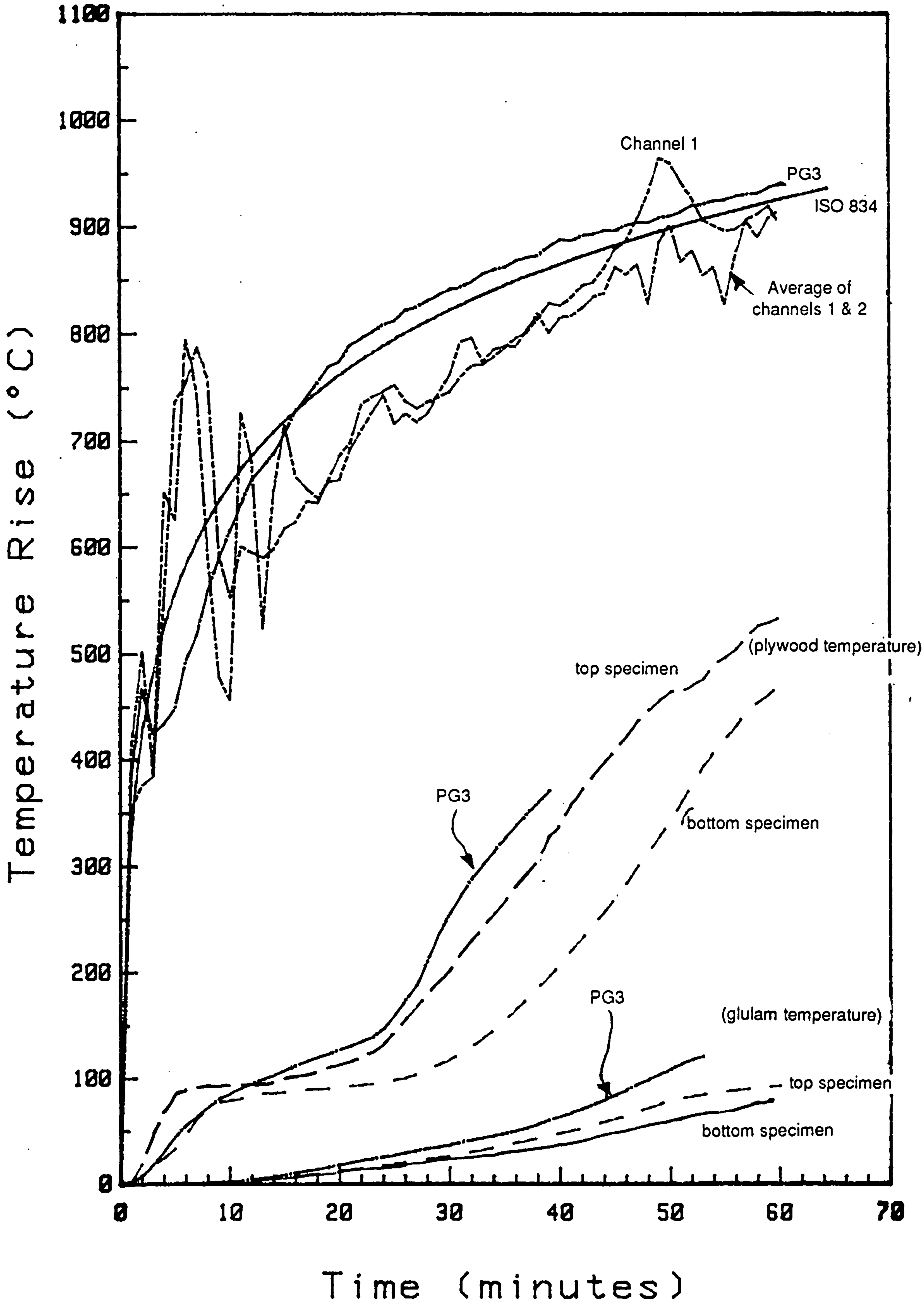


Figure 26b: Temperatures of plywood specimens - Test P2.

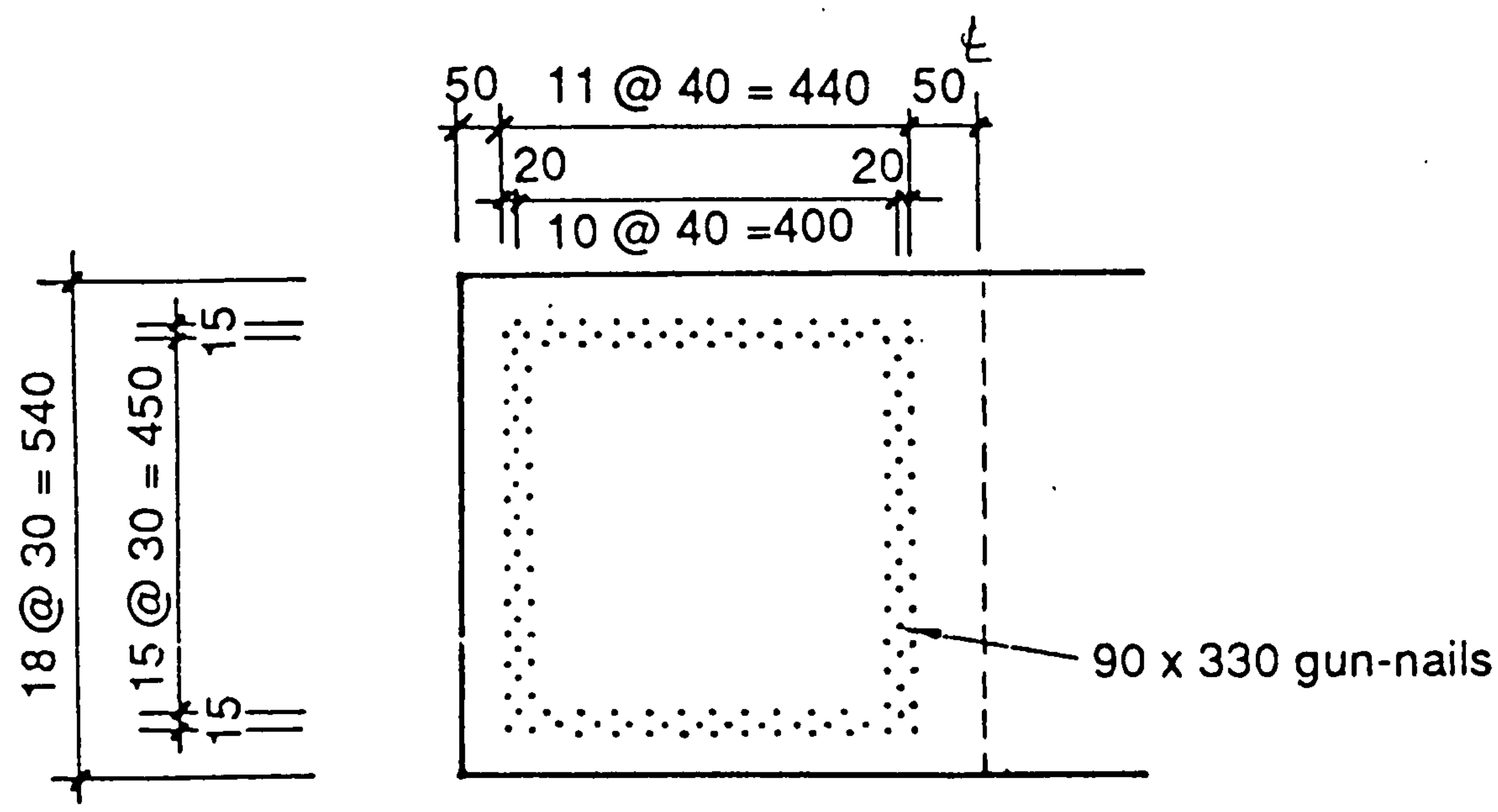


Figure 27a : 1100 x 540 x 30 plywood gusset nailing pattern

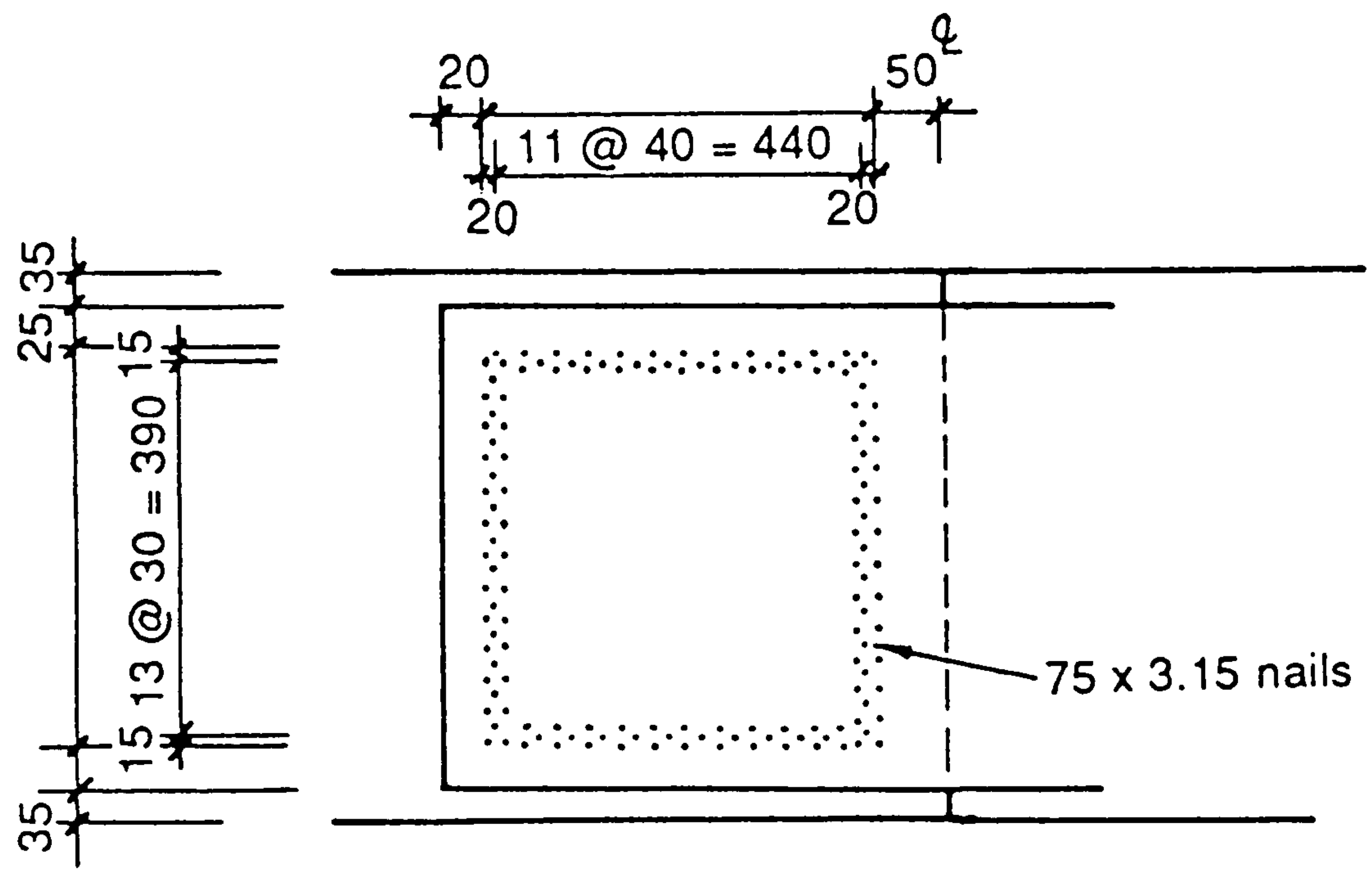


Figure 27b : 1100 x 470 x 5 steel gusset nailing pattern

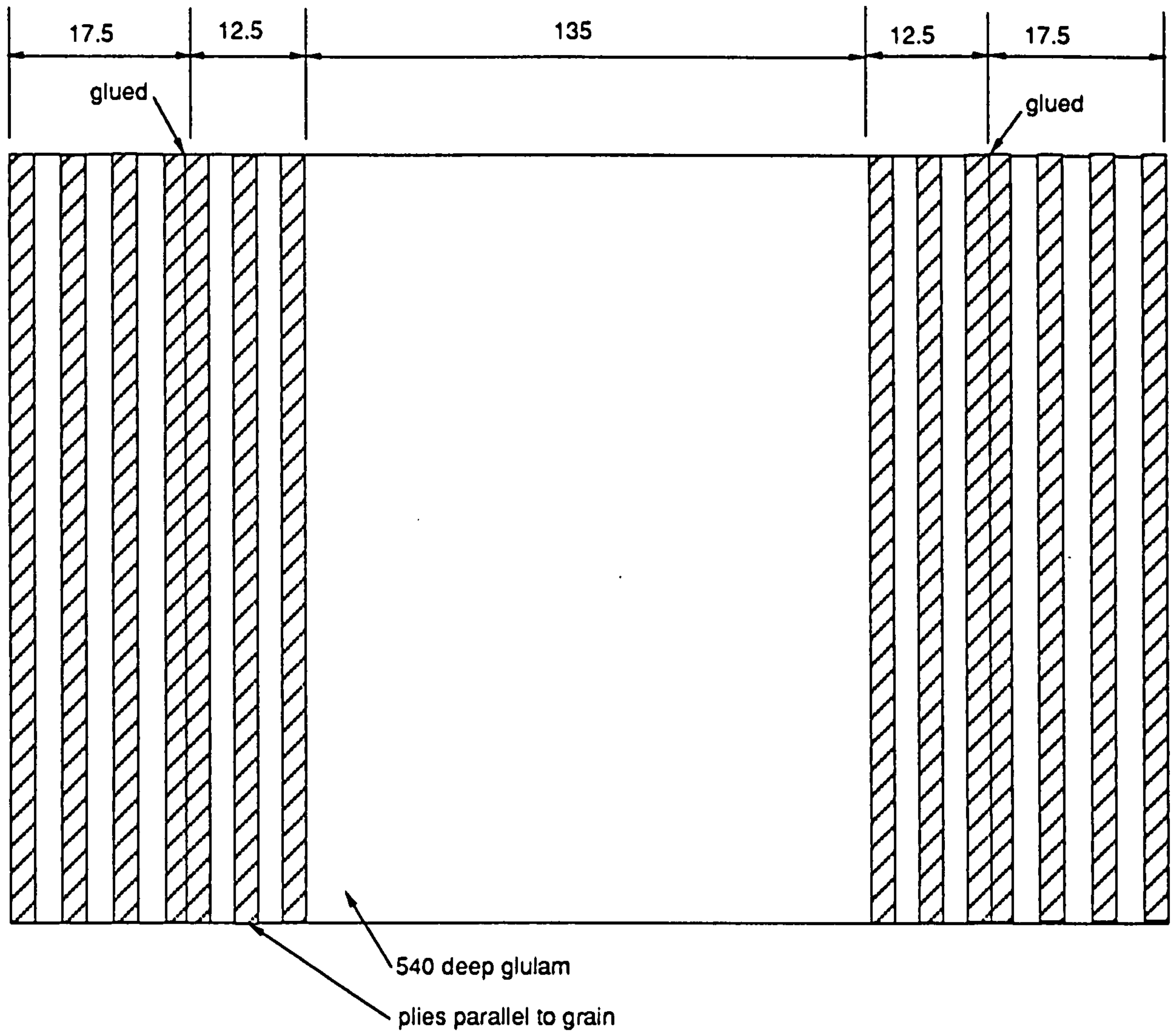


Figure 28 a : Plywood Gusset Before Test (N.T.S)

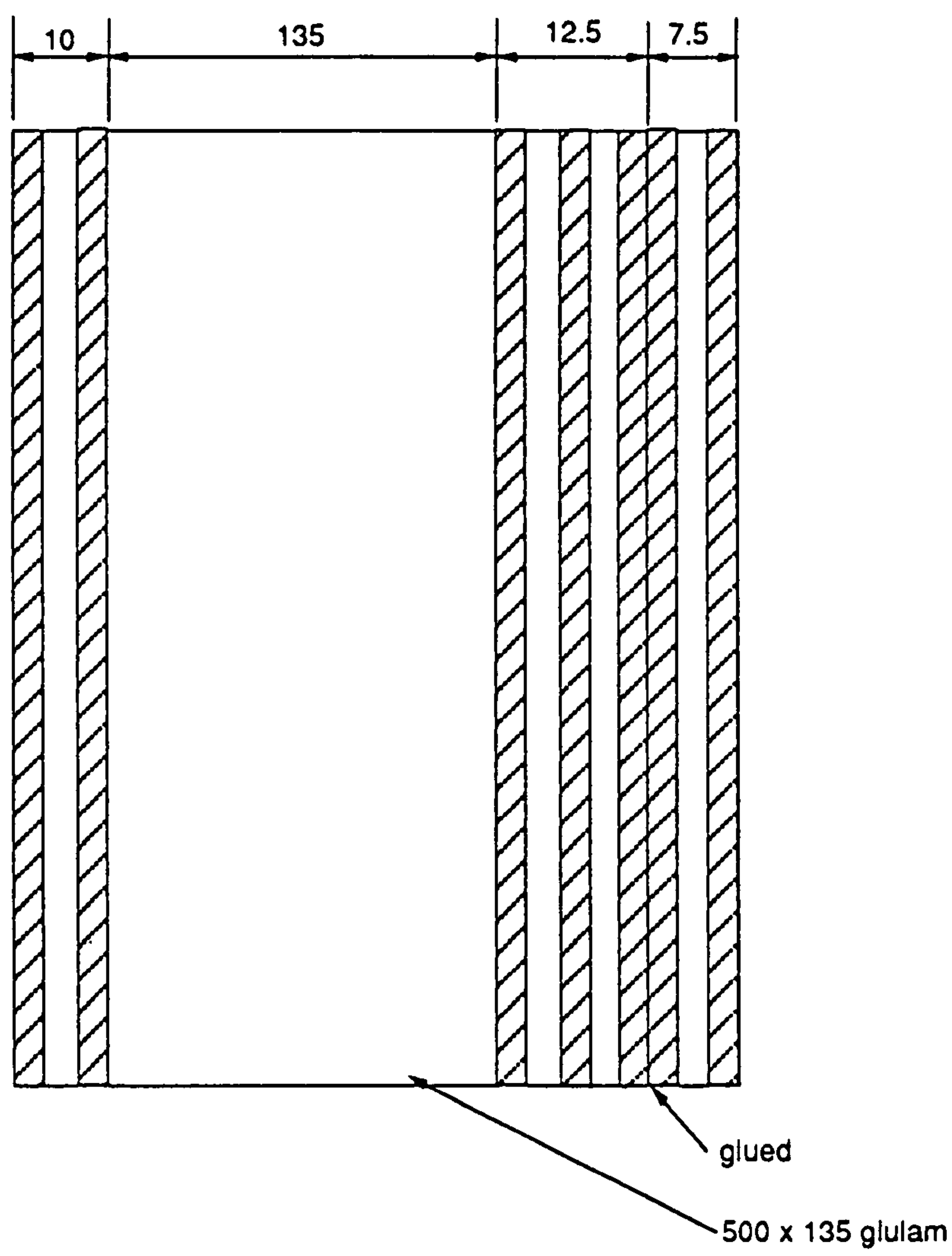


Figure 28 b : Plywood Gussets After Test (N.T.S)

Protected nailed gusset connections
for glulam members.
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