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STUDY REPORT

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DESIGN OF LOADBEARING LIGHT TIMBER FRAME WALLS FOR FIRE RESISTANCE : PART 1

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PREFACE

This report covers the first part of a research programme undertaken by (BRANZ) to develop a design method for loadbearing light timber frame walls for fire resistance. Present information and methods rely heavily on fire testing, which is expensive and inhibits the use of timber in fire-rated constructions where it could otherwise be used.

This report is primarily for engineers and architects involved in the design of loadbearing structures using light timber framing, and also to manufacturers of products used in such constructions.

BRANZ Technical Recommendation No. 9 "Design of light timber framed walls and floors for fire resistance" is now available. This publication enables the result of a single loadbearing fire resistance test to be used in the design of similarly lined walls which have differing heights and load levels.

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BRANZ Study Report SR 36 P C R Collier

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KEYWORDS

From Construction Industry Thesaurus - BRANZ edition: Charring; Deflection; Design; Failure; Fire Barriers; Fire Resistance; Fire Tests; Gypsum Plasterboard; Insulation; Integrity; Linings; Loadbearing; Models; Optimisation; Structural Adequacy; Structural Design; Studs-W; Testing; Timber.

ABSTRACT

The fire performance of loadbearing light timber framed walls is not generally well understood, and considerable professional judgement is required in their design.

This work forms the first part of a research programme, and is aimed at producing a design method where the results of a single loadbearing fire resistance test can be used to design a similarly lined wall but of different height and load level. The experiment consisted of six loadbearing fire resistance tests at various load levels and heights, one of which used a different lining system. The results showed a correlation between load and depth of charring of the studs at failure, and a relationship between load and height.

Additional design information and data was also collected, which indicated that the model may be refined further, so that a wider range of designs can be derived from limited data. This would enable fire resistance times to be predicted, resulting in considerable cost savings for designers.

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INTRODUCTION

Problem Description

Timber is under-utilised in the construction of loadbearing fire-resistant walls. To encourage timber's greater use, the industry needs advice on designs which have the required fire resistance and structural performance.

It was felt that relationships between fire resistance and wall height, timber member size and spacing, and stress levels could be established. Then, the result from one loadbearing test could be extrapolated to other walls of different stress levels and configurations.

Objectives

This work aimed to develop and validate a method of designing fire-resisting, loadbearing light timber framed walls based on a single fire resistance test to AS 1530.4 (SAA 1990) Fire resistance tests of elements of building construction.

Thus, a range of similar walls can be designed using the same lining system and having the same fire resistance, on the basis of that one test result. Variations of load and height will be catered for by changes in stud dimensions. It is not intended that the fire resistance time be altered by use of this method. That would require a more complex model and is beyond the scope of this study.

Design by a rational procedure, rather than by opinion and professional judgement, gives rise to the following advantages:

1. More certainty regarding performance of a particular construction, and hence leading to a reduction in design conservatism.

2. Easier checking of designs by approving authorities, and a reduction in discussion between designer and approving authority.

3. Time saving for designer.

4. A range of wall designs available from one test, resulting in decreased development costs for the manufacturer.

Approach

A simple model was devised based on the premise that an allowable amount of charring of the studs can occur before collapse of a wall. The model was based on previous work at BRANZ and in the literature.

Six full-scale tests were done to validate the model, and also to gather further information for later refinement.

THEORY

Theoretical Basis for Model

The present method of determining loadbearing capacity of firewalls is the "onset of char" method MP9: (SANZ 1989) Fire properties of building materials and elements of structure; also, Golding, (1986); Baber & Fowkes (1984). This method is considered to be very conservative. It is based on the premise that a loadbearing timber element protected by a sheet lining will continue to sustain its load at least until charring of the studs begins. This project sought to provide an alternative to that method.

Theoretical determination of structural fire resistance is not easy, but a general indication of structural integrity can be obtained by evaluating the loadbearing capacity of a reduced cross-section of the structural elements. This model is based on the premise that in a given element, in this instance a light timber framed wall lined with a specific lining and loaded axially, that the time to structural failure when subjected to a standard fire test will be governed by:

1) the protection offered by the exposed lining before the studs begin to char and

2) how much stud cross-section can be lost due to charring before collapse occurs.

Principle of the Model

The model itself is based on Euler's Theory as applied to eccentrically loaded columns or struts; and in particular the "secant formula", which with some modifications can be used to take into account the effects of charring on a laterally restrained stud (Figure 1) (Shigley 1972).

1) It is assumed, that at structural failure of a loaded prototype wall subjected to a fire test, a notional depth of charring of the studs will have occured. This depth can then be estimated by iteration of the char depth, against the equivalence of the maximum stress in the stud and the Modulus of Rupture of the timber.

2) It is then assumed that this notional char depth can be applied to another wall (same lining) with a different stud load and/or height. The new wall is then loaded at a level (calculated from the "secant formula") so that failure will occur at the same depth of char and time.

3) Also, this method (by iteration) can be used to design a new wall (same lining) to bear a specified load at a required height and with at least the same fire resistance as the prototype wall.

An outline of the method used is presented in Appendix B.

In each case the new wall may require a change in the stud size to accommodate the new load/height requirements.

Description of Notional Depth of Charring

The method assumes that charring would occur on three surfaces: the stud surface against the exposed lining, and on the two sides of the stud. The side of the stud against the exposed lining chars at twice the rate of the other two sides. All charring proceeds in parallel planes with respect to the original surface of the stud (Figure 1). The notional depth of charring is the depth (with these assumptions) that produces the same cross-sectional properties as those calculated from actual damaged studs.

Validation of Model

The testing programme aimed to assess if the model was reliable enough to enable a range of loaded walls to be assigned Fire Resistance Ratings (FRRs) on the basis of one fire resistance test. In addition, further data was gathered to gain a better understanding of the failure mechanisms to ensure the model worked as predicted and as a basis for further refinement.

EXPERIMENTAL

Selection and Grading of Timber

Before the start of any fire testing, consideration was given to the variation and quality of timber and how these would affect the validity of any results and conclusions.

The species and grade of timber used for the testing program was **Pinus radiata** No.1 framing grade milled from Kaiangaroa in the Tokoroa region. Two sizes were purchased: 150 x 50 mm kiln dried, with initial moisture content of 11-14%; and 100 x 50 mm air dried, with initial moisture content of 16-19% (both sets of timber were subjected to further air drying before testing however). All timber was treated with boron salts (a preservative treatment) to a retention level of 3.2 kg boric acid/m^3, Hazard Class H1, for interior service.

Visual grading eliminated timber with excessive number of knots and/or greater curvature than expected of No.1 framing and good workmanship. Discarded lengths were used for top and bottom plates and other areas of low axial stress. The timber to be used in the studs was subjected to non-destructive bending tests to determine its Modulus of Elasticity (E) (Figure 2). From knowledge of E it was then possible from previous work (Forest Research Institute (FRI), 1988); and (Princes Risborough Laboratory, 1974) to make some assumptions about the likely value of the Modulus of Rupture.

E values were then used to grade the timber into matched groups for later construction of the six test specimens.

The most flexible and stiff lengths were discarded to give groups as uniform as possible. These uniform groups were arranged so that the stud stiffness and strength were balanced along the width of each wall.

FRI data suggests that, within statistical limits, Modulus of Rupture is proportional to Modulus of Elasticity (Figure 3). On this basis mean Modulus of Rupture and 5 percentile Modulus of Rupture were 40 MPa and 24 MPa respectively, and the mean of Modulus of Elasticity from the tests was 10 GPa. These figures were then used in the calculation of failure loads.

Density, moisture content and depth x breadth measured for the timber used in the loadbearing studs are recorded in Table 1.

Load on Specimen

Determination of the specimen load was based on the method in, NZS 3603: (SANZ 1990) Code of Practice for Timber Design, as follows:

Design Stud Load = A x Fc' x K1 x K4 x K8 x K12

Where
A = area of cross-section of stud 90 x 45 mm^2
Fc'= basic working stress in compression parallel 7.1 MPa
k1 = load duration factor (dead & live) of 1.35
K4 = parallel support factor of 1.26
K8 = stability factor of 0.323 (for 3 m long 95 x 45 mm)
K12= effective length factor of 1

Design stud load for a 3 m high wall using 100 x 50 mm nominal studs.

= 90 x 45 x 7.1 x 1.35 x 1.26 x 0.323 x 1 = 15798 N.

A load of 16 kN per stud was applied to the wall in test No. 1, which was used as a base test and represented a 'design load' wall. It failed structurally at 46 minutes (see Table 2).

Construction of Specimens

All test specimens were constructed as shown in Figures 4, 5, 6. They are similar except for variations in stud size, positions of dummy studs, wall height and the addition of extra instrumentation for later tests as the need for more specific test data was recognised.

The lining material used in the first five tests was a 14.5 mm fire rated paper-faced gypsum plasterboard. For the sixth test an 18 mm medium density fibre-board lining product was used, to determine whether its behaviour was similar (on the basis of stud charring and observed structural behaviour). The linings were fixed to the studs according to the manufacturer's instructions. For the plasterboard, nails measuring 50 x 2.5 mm were spaced at 150 mm around the edges of the board and 300 mm over studs. Joints were stopped and offset by at least 600 mm on opposite sides of the wall and occurred over studs or dwangs. For the fibre-board, the instructions were similar except that 60 x 2.8 mm galvanised flathead nails were used, spaced at 200 mm on the edge of the board. Also, joints were not stopped and nails neither punched nor stopped.

Test Instrumentation

Specimens were instrumented as described below.

Temperature

Five disc-type thermocouples were attached to the unexposed face of the unexposed lining as required by test standard AS 1530.4, to monitor the insulation performance of the wall system.

Five disc-type thermocouples were attached to the unexposed side of the exposed face lining, one in the centre and one each in the centre of the four quadrants. In tests 3 to 6, extra disc thermocouples were added between the lining and the studs; and also, at 50 mm and 100 mm from the studs on the unexposed side of the exposed face lining.

In each test two dummy studs, about 600 mm long, were attached internally in the wall cavity. These were instrumented with 12 sheathed thermocouples (Figures 7, 8) to establish the pattern of charring. It is assumed that charring occurs at 300°C. The most important feature in the design of these dummy studs was that temperature loss by conduction of heat away from the thermocouple tips was prevented by running sheaths parallel with isotherms for 25 mm (same direction as wood grain in this case). Damage to the thermocouple sheaths was prevented by limiting bending to 60°. To achieve this, the studs (non-loadbearing) were cut in the centre at 60° to the grain and longitudinal holes drilled. The thermocouples were inserted into the holes and the dummy studs were glued back together with resorcinol glue.

Load Application

Load was applied by hydraulic jacks (two or three depending on the total load) using a movable platen forming the bottom sill of the specimen frame. Load was monitored using load cells connected to a continuously reading recorder.

Deflection Measurements

The out-of-plane deflection of the specimen was measured using a theodolite and staff. Measurements were taken at about 15 minute intervals, on points A to I, as shown (see Figure 4).

The vertical movement of the platen was monitored by two dial gauges, and two potentiometers connected to a data logger and a chart recorder. Impending failure of the specimen was evidenced by an increasing rate of platen movement. This movement was in advance of the inevitable reduction of load when the jacks could no longer keep up with the rate of deflection. Thus, the failure point could be determined early and the test stopped before total collapse and loss of the specimen. The furnace was then opened and the intact specimen extinguished for subsequent analysis.

Test Procedure

The frame containing the test specimen was sealed to the furnace, and the temperature and pressure conditions controlled as near as possible to those specified by the test standard AS 1530.4. Figure 9 shows the furnace temperatures for test 2, where the fire severity is calculated as 100%. Fire severity was 100% for all tests except test 6 (99%).

Results of the fire resistance tests are summarised in Table 2.

RESULTS

Failure Modes

The performance of each test specimen was assessed to the following criteria:

Structural Adequacy

Failure in relation to structural adequacy shall be deemed to have occurred when collapse occurs.

Integrity

For an element intended to separate spaces and resist the passage of flame from one space to another, failure in relation to integrity shall be deemed to have occurred upon collapse, or the development of cracks, fissures, or other openings through which flames or hot gases can pass.

Insulation

Failure in relation to insulation shall be deemed to have occurred when either:-

(a) The average temperature of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 140 °C above the initial temperature; or

(b) The temperature of any of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 180 °C above the initial temperature.

For the specimens tested failure was due to structural collapse or simultaneous failure of structural adequacy and integrity (Table 2). Insulation criteria of failure was not reached in any test and the insulation performance was similar for tests 1 to 5. The typical temperature rise is shown in Figure 10. The response of the different lining used in test 6 resulted in a more rapid temperature rise on the unexposed face.

Exposed Lining Behaviour

Figure 11 shows the temperature response of the exposed lining (non-exposed side). The three curves represent temperatures at 0, 50 and 100 mm from the stud.

Dummy Studs

The dummy studs instrumented internally with sheathed thermocouples (Figures 7, 8), monitored the rise in temperature throughout the studs. A widely accepted indicator of the onset of char is 300 °C. (Hadvig, 1981).

This figure was used to plot contours (Figure 12) on a cross-section of the stud at selected times. This then indicated the boundary between the intact and charred regions of the timber.

Deflections

The typical deflections of a tested specimen are shown in Figure 13. The curves refer to the movement of the studs at mid height, and a positive value indicates deflection away from the furnace.

Typical Behaviour of Test Specimens

The exposed plasterboard lining behaved similarly in tests 1 to 5. The recorded thermocouple data determined very closely the time when studs just began to char, and also assessed the progression of that char. In each test, the lining remained intact and attached to the studs throughout the test, even for the two tests that lasted 70 minutes. Figure 14 shows the exposed lining still attached when the furnace was opened at 70 minutes. Figure 15 shows the remains of the specimen after the fire was extinguished. Note that the exposed lining has been blasted away by the water.

Typical observations of the exposed lining over time are as follows.

10 minutes: Paper on lining completely burnt away and stopping on joints starting to crack and flake away.

20 minutes: Stopping completely flaked away and the paper tape over joints is burning; no visible opening of joints.

30 minutes: Joints opening up; lining is shrinking and pulling away from the nails; stud is visible and charring.

32-37 minutes: Flaming from joints.

40 minutes: Joints opening up about 10 mm in width; flaming continues.

50 minutes to collapse: Flaming and size of gap in joints increasing.

In test 6, with the wood-based lining, behaviour was noticably different. This is because the exposed lining was completely burnt away at about 25 minutes, compared with gypsum lining still intact at 70 minutes. Once the wood-based lining had burnt away the studs and originally unexposed lining were subjected to full furnace temperature of 800 to 900°C, compared to only 300 to 400°C for the plasterboard-lined walls.

The furnace was opened and the burning wall extinguished at the end of each test. After the wall and furnace cooled, selected samples were removed from the wall and the char scraped away to examine the remaining cross-sections. The actual charring and that indicated by the instrumentation, was compared with the depth of charring expected to result in failure. The parameters used to assess this were; depth of char C, cross-sectional area A, and second moment of area I. The method used to measure C, A and I is described in Appendix A.

The progression of the char depth, was measured at selected time intervals using the data from internal thermocouples in the dummy studs and plotted on Figure 16. The bands indicate upper and lower limits of char encountered; the upper limit being with timber of 12% moisture content against a joint in the lining, the lower limit with 16% moisture content timber against continuous lining. A straight line with a gradient corresponding to a charring rate of 0.6 mm/min (the accepted figure for charring rate of timber in MP9: 1989) is superimposed on the graph for comparison purposes.

ANALYSIS

Lining Performance

If the predominant cause of failure is structural collapse, the performance of the exposed lining has a direct bearing on when structural failure will occur.

Protection of the Studs by the Exposed Lining

The temperature response of the inner face of the exposed lining illustrated in Figure 17 shows that it takes about 25 minutes before the inner face of the exposed lining reaches a temperature of 300°C (ambient temperature 15°C plus a rise of 285°C), when charring of the studs would be expected to begin. However, temperature measurements of the lining-to-stud interface showed (Figure 11) that there is a time lag of about 5 minutes. This is because heat is conducted into the studs, keeping the lining-to-stud interface cooler than the adjacent lining and delaying the start of charring. This means that the plasterboard lining used in the tests provided protection to the studs for about 30 minutes before charring begins.

The behaviour of the wood-based lining was similar up until about 25 minutes; thereafter, the lining temperature increased rapidly, indicating that it had completely burnt away, (Figure 17). The time lag observed with the plasterboard lining (Figure 11) was not evident with the wood-based lining.

Instrumented dummy stud results show that the charring rate in test 6 with the wood-based lining was about 1.2 mm/min compared with 0.4 to 0.5 mm/min for tests 1 to 5. The charring rate differences illustrate the effects of the two types of lining. Figure 12 shows the typical progression of char across a stud lined with the plaster-board lining at 10 minute intervals (these contours were drawn from the information gathered by the instruments in the dummy studs.)

Charring of the Studs

The ability of studs to continue to sustain their load, while undergoing a loss of section due to charring, determines when structural collapse will occur. Using the proposed model it is possible to calculate how much charring a stud can be expected to sustain before collapse; this was compared with collapsed specimens from actual tests.

The results in Tables 3, 4 and 5 (from tests 3, 2, and 5, respectively) indicate a close correlation between the instrumented studs and the ideal case of a stud against continuous lining and away from the influence of the nails used to attach the lining. Significantly greater charring of studs was noted close to nails and on the lining joints. These differences in char depth can be seen in Figure 18. The extent of charring at failure, for the ideal case of a stud against continuous lining, can be seen in Figures 19 and 20.

The results of tests 1, 4 and 6 are not analysed to the same extent, because either the specimens were not extinguished in time (test 1 and 6) to allow useful samples to be salvaged, or failure occurred by lateral buckling of studs (test 4).

The mean time to "onset of char" (char at a depth of 5 mm in studs) measured with 10 thermocouples in tests 1 to 5, was 43 minutes (range 39 - 48 minutes).

Comparison of Actual and Predicted Charring at Failure in Relation to Loadbearing Capacity.

To assess charring depth of studs, representative samples were taken for each test using the same criteria as above. The predicted range of char depth required for failure to occur was calculated using the model based on eccentricities of 0 and 15 % with a Modulus of Rupture of 40 MPa and a Modulus of Elasticity of 10 GPa. The predicted and measured ranges of charring were then compared.

Table 6 compares predicted and measured charring at structural failure. It is noteworthy that for all tests except test 4, the ranges of values intersect. The important trends to note in the table are that:

1) The higher char figures in the predicted ranges actually represent the 0% eccentricity of loading condition (which is more likely given the care taken in specimen construction).

2) The lower char figures in the measured range refer to the lining away from nails, avoiding the regions where increased localised charring (necking), caused by heat conduction along the nails, occurs.

3) The higher char figures in the measured range refer to the necking caused by nails and knots in localised regions under a compressive load (being on the charred, concave side). Although this effect contributes to the observed necking, it is not expected to create a serious weakness, nor does it contribute significantly to the overall deflection.

4) The lining joints result on average in an increase in measured char depth of 5 mm or less. The mean char depth, ignoring effects of nails, is about 2.5 mm greater than the lower end of the range.

Close correlation exists between the mean of the measured char and the upper limit of the predicted range (corresponding to 0 % eccentricity), for all tests except test 4. The correlation coefficient is 90 % (least squares regression).

Test 4 failed earlier than expected. It was observed that the studs, unrestrained by dwangs, had buckled and twisted laterally once the exposed lining had lost its strength. However, the unexposed lining continued to restrain lateral movement of the studs.

A further comparison is shown in Table 7, but these figures assume failure occurs at an axial stress of 24 MPa (the lower 5 percentile limit) instead of 40 MPa. These results show timber strength does not have a marked effect on the depth of charring required for collapse to occur. Similarly, the initial eccentricity does not influence significantly the allowable depth of char.

However, Modulus of Elasticity does have a marked effect, and reductions in Modulus of Elasticity cause rapid reduction in the char needed for failure. This can be explained by considering a stud that has already begun to buckle under load. Any further reduction in stiffness will cause it to deflect even more, increasing its bending moment, leading to rapid failure. Table 8 illustrates the marked reduction in the predicted char depth if the Modulus of Elasticity is 8 GPa, which is the value for No. 1 framing radiata pine listed in table 2 of NZS 3603.

In order to determine the effects of heating on loadbearing walls, consideration needs to be given to the effect of temperature on the compressive stength and elasticity on uncharred areas of timber. This will be treated in a later section.

DISCUSSION

Deflections

Deflection of the wall was monitored in all tests. Provided load is below a critical level, then it is likely to deflect away from the fire eventually, even if it deflects towards the fire initially. Figure 13 shows the typical sequence of deflections of the mid heights of the studs.

This can be explained by considering the likely sequence of events as the wall is tested.

1) Initially, the studs undergo a differential thermal expansion due to the higher temperature on the exposed side; causing bowing towards the furnace.

2) The initial deflection is reversed subsequently as the exposed side of the studs shrinks as the moisture content reduces due to increasing temperature. It was also observed that the exposed side of the plasterboard lining used in tests 1 to 5 shrunk on heating as well, contributing further to this outward deflection.

3) Finally, the exposed side of the studs begin to char, undergoing a loss of cross-section and strength. This, combined with the vertical load and the deflection away from the furnace, generates a bending moment causing the observed rapid increase in deflection away from the furnace.

In test 1, where the wall failed towards the furnace, it is assumed that the load was sufficiently high to prevent the deflection changing direction once it started.

The contribution of lining to load capacity was ignored in this study, as it was thought that it did not have a significant effect in comparison to stud strength, especially once fire had degraded the exposed lining.

Lining Performance

The type of the lining material and the protection that it offers to the studs (in terms of the time interval before charring commences and the rate of temperature rise in the vicinity of the studs) can have a significant influence on the final fire resistance for the system.

Also, the length of time the exposed lining remains intact and attached to the studs has a dramatic influence on the final fire resistance. The difference in performance between the plaster-based and wood-based linings illustrates this. Once the wood-based lining had burnt completely away (after about 25 minutes), the instrumented studs indicated an increased rate of char of about 1.2 mm/min. Structural failure occurred shortly thereafter.

Vertical Lining Joints

The vertical joints in the lining material, although stopped and taped, tended to open up and tear around the nails during the tests. This could be caused by shrinkage of the lining (if it occurs) and an initial inwards deflection of the wall. Opening of gaps will initiate earlier charring of the studs, causing some reduction in fire resistance.

Other lining materials may behave differently from the two tested products. Thus, it is important that a prototype test is conducted for for each lining.

Influence of Dwangs

The restraining influence that dwangs have on lateral deflection of the studs is only apparent when exposed lining has lost its strength or fallen away. Without dwangs the lining material will initially restrain the studs; once one side has lost its strength, the studs have a tendency to twist and buckle laterally, even if still restrained on the one side by the unexposed face lining. This can lead to wall collapse earlier than expected. It is therefore essential that dwangs be included in all fire-resisting constructions to ensure that wall behaviour follows predicted patterns.

Table 2 shows which test specimens had dwangs and which ones did not. Test 4, which was an extrapolation of test 3, failed earlier than expected. This was because the studs, unrestrained by dwangs, rotated as well as deflected away from the furnace. The depth-to-width ratio of the studs is the important consideration, 150 x 50 mm studs having a greater requirement for dwangs than say 100 x 50 mm studs, due to their greater ratio of second moment of areas about the principal axes.

Stud Spacing and Sizes (King, 1987)

The stud spacing in all tests was 600 mm. If required, this spacing could be reduced to give a wall greater load carrying capacity. It is not permissible however, to test a wall at a lesser spacing (e.g.,400 mm), and then extrapolate this to say 600 mm for a lighter loaded wall. This is because the lining will be fixed across a greater span and therefore will not be as well restrained. This could result in the exposed lining falling away earlier, reducing the fire resistance.

Similarly, it is permissible to increase the width of a stud in extrapolating to a new wall, but it cannot be reduced. This is because the proportional rate of loss of cross section will be increased and the ability of the nails to remain in the stud, and attach the lining to the stud, will be reduced.

Stud depth or space between linings cannot be reduced. Comparing the unexposed lining temperatures of tests 2 and 5 at structural failure (Table 2), indicates that the time to insulation failure would be reduced if the stud depth is reduced. Also, faster temperature rise in the cavities may increase charring rate of the studs, and also allow the nails securing the lining to pull out sooner; all may reduce the time to failure. Comparison of tables 4 and 5 indicates a greater depth of charring corresponding to the reduced stud depth.

The Effect of Knots and Elevated Temperature on Timber Performance

Knots in timber, although creating a weakness, often char at a slower rate than the surrounding timber. This can either strengthen or weaken the stud, depending on if charring is inhibited by a knot, or the remaining cross section contains a knot (see Figure 18). Noren (1988) concludes that knots do not significantly affect failure time in loaded timber; indeed, he found no significant difference between high grade structural timber with none or only a few knots, and knotted timber representative of low grade structural timber.

Noren (1988) quantified the loss of timber strength at elevated temperatures and found that the remaining strength ranged between 25 to 50% depending on the cross section remaining at failure, which in turn depends on the level of load. Noren also noted that rupture, due to bending under fire exposure, was caused by compression failure. Figure 21 shows that failure is, in many cases by compression.

Gammon (1987) presents several models for the degradation of compressive strength and Modulus of Elasticity at elevated temperatures. These are for application to his computer simulation of wood frame wall assemblies when exposed to fire. The loss of compressive strength is generally a linear relationship where remaining strength is 50 and 20% at temperatures of 200 and 288°C, respectively. Charring is considered to occur above 288°C resulting in complete loss of strength. From the above discussion and Tables 7 and 8 it is evident that the charring depth required for failure to occur is not affected significantly by strength loss. This is reinforced by the knowledge that thermal conductivity of wood is low, and that the temperature gradient below the char layer is high. This results in significantly lower temperatures at the centre of a stud, an essential consideration in timber design for fire and the reason for the relatively small loss in overall strength.

However, it is worth noting that if the lining thickness is increased or multiple sheets are used, then the rate of temperature rise within the studs will be slower, but will occur over a longer period. This is thought to result in a lower temperature gradient below the char layer and greater heating of the stud core, causing a greater loss of strength in the stud.

This phenomenon is not likely to affect adversely application of the proposed model, as the comparison between a prototype and an extrapolated design is based on the equivalence between walls of the combined effects of the degree of charring and strength loss of the studs. This assumption is valid, because the intent of the extrapolation method is to design a new wall which can be loaded to a level so that its time to failure will be at least equivalent to the prototype test.

Modulus of Elasticity is not affected by elevated temperatures as much as strength. Knudson, (1973) reports no loss of elasticity up to 300°C for timber of 12% moisture content, and Preusser, (1968) reports that 75 % of elasticity remains at 250 deg C. This is important because a reduction of E can reduce significantly the allowable charring necessary for structural collapse to occur.

Figure 23 illustrates the relative effects of variations in eccentricity of loading, compressive strength, and Modulus of Elasticity on the charring required for failure to occur. In conclusion, there is increased confidence in the use of this model because the expected differences in fire performance of various wall types will be very small.

Other Influences on Performance

Other influences on performance are:

1. Nails used to attach the lining will conduct heat from the fire exposed side and accelerate local charring of the studs causing necking.

2. Some lining materials shrink on heating whereas others expand. This influences the opening of gaps and the exposure of studs.

3. The lining may make a small contribution to the structural performance of the wall depending on whether it is plaster-based, wood-based, or another material, and also whether it shrinks or expands on heating.

Limitations of Model

Models such as this begin with an idealised approach which may ignore practicalities which are difficult to quantify. If attempts are made to cater for these realities, a very complex and often unworkable model may result, which is no more reliable than a more basic model. By taking a macroscopic approach to testing and predicting the performance of loaded walls, unquantifiable effects, many of which tend to cancel each other out, are all catered for. This assumes there is sufficient similarity between the prototype and the extrapolation.

Future Work

Future work could look at further refinements to the model. Work should concentrate on the establishment of empirical relationships to predict the performance of variations to existing and new wall systems. Because the building code now permits more use of light timber framed constructions, future research should look at the above design techniques with a view to using them in multi-storey buildings.

CONCLUSIONS

(1) These and previous tests developed and validated a model to reduce dependence on full scale testing.

In addition, further knowledge on the behaviour of loadbearing and non-loadbearing walls was accumulated which will form the basis of future work.

(2) Future work will benefit from the increased knowledge of the behaviour of loadbearing and non-loadbearing walls.

(3) There exists a reliable relationship between the loadbearing capacity at structural failure and the uncharred remains of the stud.

(4) The expected variations in timber properties had no serious effect on the performance of fire rated wall systems, provided that any construction is always within the theoretical limitations of the model.

Application of the Model

This work is based on the theory that fire resistance of a loadbearing wall is dependent on the time taken for the exposed lining to cease providing protection to the studs. Secondly, the theory also depends on the length of time before charring of the studs in loadbearing walls causes structural collapse.

This model is the basis of BRANZ Technical Recommendation No. 9: Design of light timber framed walls and floors for fire resistance.

The procedure involves using information gained in one fire resistance loadbearing light timber framed wall test, to design additional walls. The new walls will have the same lining arrangement, but different load levels and dimensions. Hopefully these will have the same or better fire resistance than the prototype. How the data gained in a prototype test can be used to design a new wall is shown in Apppendix B.

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APPENDIX A

Assessment of Charring in Studs, Actual and Indicated

The method used numerical integration which involved placing a transparent grid graduated in mm (Figure 24), over the charred cross-section; or, over a contour plot drawn to scale on graph paper from the recorded data from the instrumented dummy studs at the elapsed time required.

The uncharred stud area was then counted in 2 mm^2 wide intervals relative to a base line, and the figures entered into a computer program which calculated 2nd moment of area I, neutral axis location y, cross-section area A and the depth of char C.

The program used is as follows.

```
10     PRINT "Charring of cross-section"
20     PRINT "Original Stud Size"
30     INPUT "Original Depth";DE
40     INPUT "Original Breadth";BR
50     PRINT "Enter Charred Section"
60     FOR B=2 TO BR STEP 2
70     PRINT "Enter Remaining Depth";"(";B;")":INPUT D
100    REM " 2nd Moment of Area"
110    J=J+D^3*2/3
120    REM "Cross Sectional Area"
130    A=A+D*2
140    REM "1st Moment of Area"
150    C=C+D*2*D/2
160    NEXT B
170    REM "Neutral Axis"
180    Y=C/A
190    REM "2nd Of Area About Neutral Axis"
200    I=J-A*Y^2
210    PRINT "2nd Moment Of Area",I,"%=",I/(BR*DE^3/12)*100
220    PRINT "Neutral Axis", Y
230    PRINT "X Sect Area",A,"%=",A/(BR*DE)*100
240    REM "Depth of Charring"
250    C1=0:C2=BR
260    IF ABS(C1-C2)<=.0001 THEN 320
270    C=(C1+C2)/2
280    K=(BR-C)*(DE-C)^3/12-I
290    IF K>0 THEN 310
300    C2=C:GOTO 260
310    C1=C:GOTO 260
320    PRINT "Char Depth",C
```

APPENDIX B

The extrapolation method

The following is a BASIC programme listing, similar versions of which were used to analyse the test data and generate the tables and graphs which form the basis of Technical Recommendation No.9. Two worked examples are included to demonstrate how a new design can be extrapolated from a prototype test result.

A design factor is included in this procedure. This involves increasing the assumed eccentricity of loading from 5% for the prototype wall to 10% for the extrapolated wall. This takes account of the difference between the controlled conditions under which a prototype will be constructed in a test laboratory, and the on-site conditions under which the extrapolated wall will be built.

The term "charfactor", which appears in the programme listing and Technical Recommendation No.9 is equivalent to the char depth in mm as defined by Figure 1. It is intended to be the linkage between the prototype and extrapolated walls, by providing an arbitrary measure of the fire damage at the time of failure.

```
10 PRINT "DESIGN OF LIGHT TIMBER FRAMED WALLS FOR FIRE
RESISTANCE"
20 PRINT "Determination of charfactor"
30 'Timber properties assumed for both prototype and extrapolated walls
40 E=8E+09'Modulus of elasticity Pa
50 S(0)=2.4E+07'Max permissible stress Pa
60 EX=5'Assumed eccentricity %
70 PF=10 'Pressure in furnace Pa
80 ST=.6 'Stud spacing m
90 PRINT "Enter Test Data From Prototype Test:"
100 INPUT "Actual Stud Depth  mm ";DA
110 DA=DA/1000
120 INPUT "Actual Stud Breadth mm ";BA
130 BA=BA/1000
140 INPUT "Wall Height m";L1
150 INPUT "Test Load per Stud kN";P1
160 L=L1-2*BA 'Stud height allowing for top and bottom plates
170 'Iteration to find "Charfactor" or char depth mm at failure (max
    permissible stress)
180 C(1)=0:C(2)=BA
190 IF ABS(C(1)-C(2))<=.00001 THEN 270
200 C=(C(1)+C(2))/2
210 X=EX/100*DA 'Eccentricity
220 GOSUB 2000
230 IF Y>3.1416 THEN 250
240 IF S<S(0) THEN 260
250 C(2)=C:GOTO 190
260 C(1)=C:GOTO 190
270 CF=C*1000
280 PRINT "Charfactor of test specimen =";CF
1000 PRINT
1010 PRINT "Design of Extrapolated Wall"
1020 EX=10 'Assumed eccentricity of loading for extrapolated wall.
1030 PRINT "Determine max allowable stud load"
```

```
1040 INPUT "Nominal Stud Depth mm";D
1050 INPUT "Nominal Stud Breath mm";B
1060 INPUT "Wall Height m";L2
1070 INPUT "Charfactor or char depth in mm";C
1080 C=C/1000
1090 BA=(B-5)/1000 'Approximate actual stud depth.
1100 DA=(D-10)/1000 ' Approximate actual stud breadth.
1110 L=L2-2*BA 'Stud height allowing for top and bottom plates.
1120 X=EX/100*DA 'Actual eccentricity of loading in stud.
1130 I=(BA-C)*(DA-C)^3/12 'Second moment of area of stud.
1140 'Iteration to determine max load.
1150 P(1)=0
1160 P(2)=3.1^2*E*I/L1^2/1000!-50*L1*DA*BA 'Upper limit of load.
1170 IF ABS (P(1)-P(2))<=.0001 THEN 1230
1180 P1=(P(1)+P(2))/2
1190 GOSUB 2000
1200 IF S<S(0) THEN 1220
1210 P(2)=P1:GOTO 1170
1220 P(1)=P1:GOTO 1170
1230 PRINT "Maximum Allowable Stud Load =";P1;"kN"
1240 PRINT "Try another stud y/n ? "
1250 A$=INKEY$
1260 IF A$="y"OR A$="Y" THEN 1030
1270 IF A$="n"OR A$="N" THEN END
1280 GOTO 1250
2000 'Subroutine
2010 P=(P1+50*L*DA*BA)*1000'Total load on wall including approx self
     weight
2020 M=PF*L/2*ST*L^2/8 'Moment generated by pressure.
2030 I=(BA-C)*(DA-C)^3/12 'Second moment of area.
2040 A=SQR(P/(E*I)) 'Alpha as in secant formula.
2050 R=.289*(DA-C) ' Radius of gyration.
2060 S=P/((BA-C)*(DA-C))*(1+(C/2+X)*(DA-C)/2/R^2*1/COS((A*L)/2))+M*
    (DA-C)/2/I 'Secant formula
2070 Y=A*L
2080 RETURN
```

Example 1

```
DESIGN OF LIGHT TIMBER FRAMED WALLS FOR FIRE RESISTANCE
Determination of charfactor
Enter Test Data From Prototype Test:
Actual Stud Depth  mm ? 90
Actual Stud Breadth mm ? 45
Wall Height m? 3
Test Load per Stud kN? 8
Charfactor of test specimen = 13.84827

Design of Extrapolated Wall
Determine max allowable stud load
Nominal Stud Depth mm? 150
Nominal Stud Breath mm? 50
Wall Height m? 4
Charfactor or char depth in mm? 14
Maximum Allowable Stud Load = 17.48686 kN
```

Example 2

```
DESIGN OF LIGHT TIMBER FRAMED WALLS FOR FIRE RESISTANCE
Determination of charfactor
Enter Test Data From Prototype Test:
Actual Stud Depth  mm ? 150
Actual Stud Breadth mm ? 50
Wall Height m? 4
Test Load per Stud kN? 16
Charfactor of test specimen = 22.69898

Design of Extrapolated Wall
Determine max allowable stud load
Nominal Stud Depth mm? 150
Nominal Stud Breath mm? 75
Wall Height m? 5
Charfactor or char depth in mm? 23
Maximum Allowable Stud Load = 13.87126 kN
```

Table 1: Timber Properties - Range of values				
Test Number	Dry Density kg/m³	Moisture Content %	Depth mm	Thickness mm
1	344-517	15.0-16.5	88-90	44-46
2	390-585	13.5-16.0	88-90	44-46
3	398-518	15.0-16.0	88-90	44-46
4	457-497	12.0-15.0	138-140	44-46
5	437-526	12.0-13.0	138-140	44-46
6	332-476	14.0-17.0	88-90	44-46

Table 2: Validation Test Results							
Test Number	Stud Size nominal(mm)	Load per Stud(kN)	Wall Height(m)	Dwangs Y/N	Failure Time(min)	Failure mode	Failure Temp(4)
1	100 x 50	16	3	N	46	S,N (1)	71
2	100 x 50	8	3	N	70	S (2)	95
3	100 x 50	10	3	N	60	S (2)	79
4	150 x 50	40	3	N	40	S,N (2)	65
5	150 x 50	20	4	Y	71	S,N (2)	81
6	100 x 50	16	3	Y	30	S (2)(3)	70

Failure Modes: S - Structural Adequacy, I - Insulation, N - Integrity

(1) Failed inwards towards furnace

(2) Failed outwards from furnace

(3) Wood-based lining material

(4) Average temperature rise of the unexposed face of wall °C.

Table 3: Stud cross-sections (100 x 50 mm) after 60 minutes (test 3)					
Sample Location *	Initial Dimensions (mm)	X-Sect Area (mm^2)	Second Moment Of Area (mm^4) x 10^{-5}	Neutral Axis Location (mm)	Equivalent Char Depths (mm)
Initial	90 x 45	4050	27.3	45	0
1	90 x 45	2524 (62.3%)	10.4 (38.1%)	34.3	15.2
2	90 x 45	2272 (56.1%)	9.06 (33.2%)	33.9	17.0
3	90 x 45	1932 (47.7%)	5.24 (19.2%)	27.1	23.6
4	90 x 45	2216 (54.7%)	8.09 (29.6%)	32.1	18.5
5	90 x 45	2324 (57.4%)	8.37 (30.6%)	31.7	18.0
6	90 x 45	2538 (62.7%)	10.71 (39.2%)	35.07	14.8
				mean	17.8

* Locations of samples in tables 3 to 5

1 Dummy stud #1 against continuous lining

2 Dummy stud #2 against continuous lining (except in test 5 against a horizontal joint)

3 Stud against lining joint close to nails

4 Stud against lining joint remote from nails

5 Stud against continuous lining close to nails

6 Stud against continuous lining remote from nails

Table 4: Stud cross-sections (100 x 50 mm) after 70 minutes (test 2)

Sample Location *	Initial Dimensions (mm)	X-Sect Area (mm^2)	Second Moment Of Area (mm^4) x 10^{-5}	Neutral Axis Location (mm)	Equivalent Char Depths (mm)
Initial	90 x 45	4050	27.3	45	0
1	90 x 45	2206 (54%)	8.80 (32.2%)	31.7	17.4
2	90 x 45	2030 (50.2%)	6.69 (24.5%)	29.9	20.8
3	90 x 45	1290 (31.8%)	2.33 (8.5%)	21.4	31.2
4	90 x 45	1676 (41.4%)	4.48 (16.4%)	26.7	25.2
5	90 x 45	1804 (44.5%)	4.58 (16.7%)	26.2	25.0
6	90 x 45	2024 (49.9%)	6.64 (24.3%)	29.8	20.9
				mean	23.4

*- Sample Location (see bottom of table 3)

Table 5: Stud cross-sections (150 x 50 mm) after 70 minutes (test 5)					
Sample Location *	Initial Dimensions (mm)	X-Sect Area (mm^2)	Second Moment Of Area (mm^4) x 10^{-6}	Neutral Axis Location (mm)	Equivalent Char Depths (mm)
Initial	140 x 45	6300	10.29	45	0
1	140 x 45	4138 (65.6%)	4.30 (41.7%)	52.2	17.2
2	140 x 45	3568 (56.6%)	2.80 (27.2%)	45.4	23.7
3	140 x 45	3230 (51.2%)	2.52 (24.5%)	46.5	25.1
4	140 x 45	4110 (65.2%)	4.36 (42.3%)	54.5	16.9
5	140 x 45	4058 (64.4%)	3.61 (35.1%)	51.1	20.0
6	140 x 45	4576 (72.6%)	4.97 (48.3%)	55.8	14.7
				mean	19.6

*- Sample Location (see bottom of table 3)

Table 6: Comparison of Predicted and Measured Char at Failure Based on a Modulus of Rupture of 40 MPa and Modulus of Elasticity 10 GPa			
Test Number	Predicted Range (mm) ¤	Measured Range(mm)	Char Mean(mm)
1	7-10	8 *	8
2	16-18	(17-31)	24
3	13-16	(15-24)	18
4	9-15	7 Ø	7
5	14-18	(15-25)	20
6	7-10	(10-18)	13

* Specimen could not be salvaged in order to measure charring at failure.

Ø Specimen failed by lateral buckling of studs.

¤ eccentricity of loading, 15% and 0% respectively.

Table 7: Comparison of Predicted and Measured Char at Failure Based on a Modulus of Rupture of 24 MPa and Modulus of Elasticity 10 GPa			
Test Number	Predicted Range (mm) ¤	Measured Range(mm)	Char Mean(mm)
1	5-9	8 *	8
2	14-17	(17-31)	24
3	11-15	(15-24)	18
4	4-13	7 Ø	7
5	11-16	(15-25)	20
6	5-9	(10-18)	13

* Specimen could not be salvaged in order to measure charring at failure.

Ø Specimen failed by lateral buckling of studs.

¤ eccentricity of loading 15% and 0% respectively.

Table 8: Comparison of Predicted and Measured Char at Failure Based on a Modulus of Rupture of 40 MPa and Modulus of Elasticity 8 GPa			
Test Number	Predicted Range (mm) ¤	Measured Range(mm)	Char Mean(mm)
1	4-7	8 *	8
2	14-16	(17-31)	24
3	11-13	(15-24)	18
4	7-12	7 Ø	7
5	11-15	(15-25)	20
6	4-7	(10-18)	13

* Specimen could not be salvaged in order to measure charring at failure.

Ø Specimen failed by lateral buckling of studs.

¤ eccentricity of loading 15% and 0% respectively.

Note: There is a small time interval between the specimen failing and opening the furnace to extinguish the fire, typically 2-3 minutes. In this small time interval the studs continue to char and therefore it is expected the measured char will be a little higher, typically 1-2 mm. However there are several other variables which influence the behaviour, and these are covered in the discussion.

"Secant Formula" as applied to eccentrically loaded studs (in a wall) including the effects of charring and furnace pressure:

$$\sigma_{max} = \frac{P}{A}[1 + \frac{ec}{r^2}\sec(\frac{\alpha L}{2})] + \frac{M(D-C)}{2I}$$

where:

σ_{max} = maximum permissible stress in stud

P = load per stud

A = $(D-C)(B-C)$ x-sect area of stud

D = depth of stud

C = char depth in stud

B = breadth of stud

e = $\frac{C}{2} + X$ actual eccentricity of loading

X = initial eccentricity of loading (assumed)

c = $\frac{D-C}{2}$

r = $0.289(D-C)$ radius of gyration

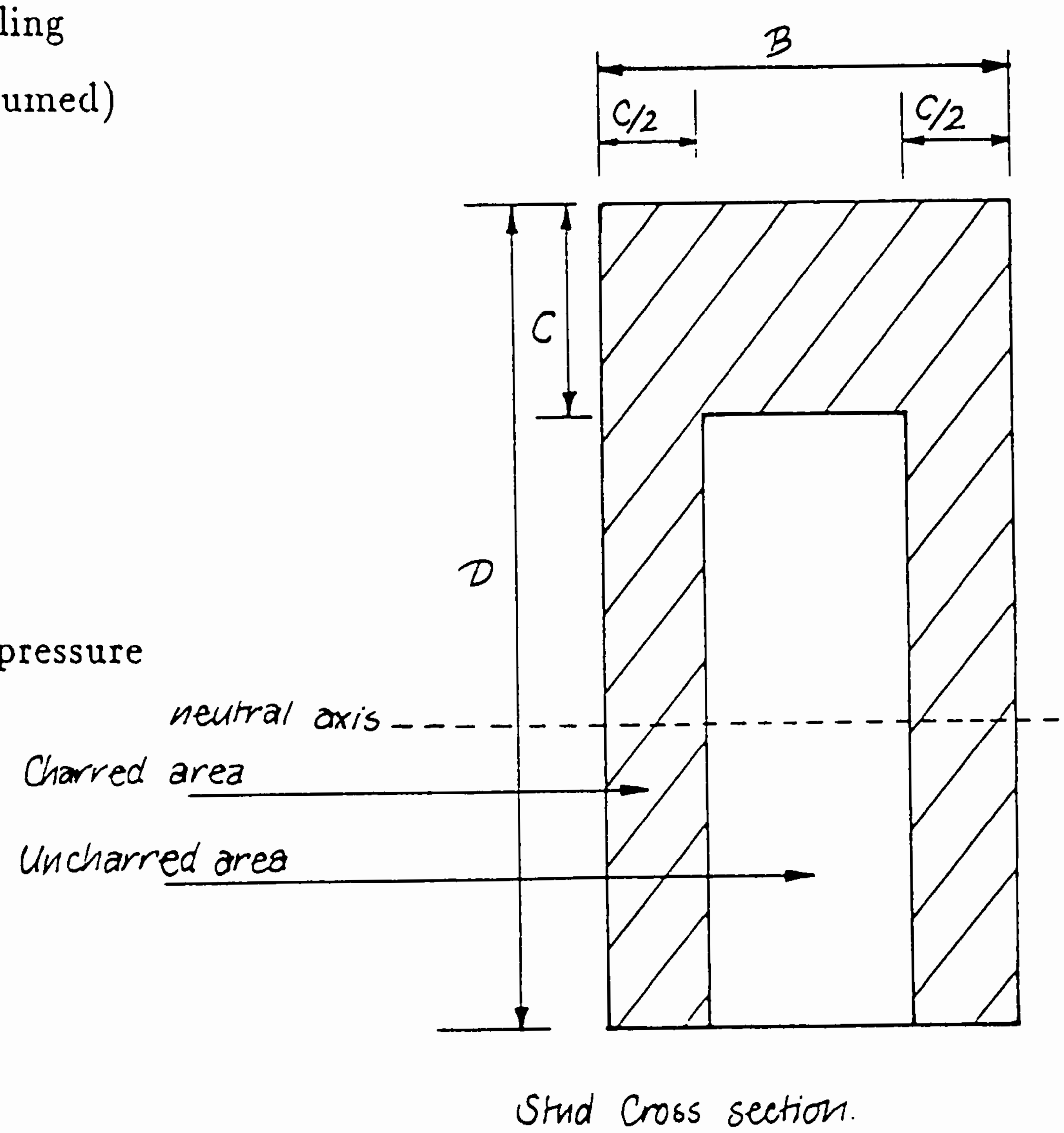
α = $\sqrt{\frac{P}{EI}}$

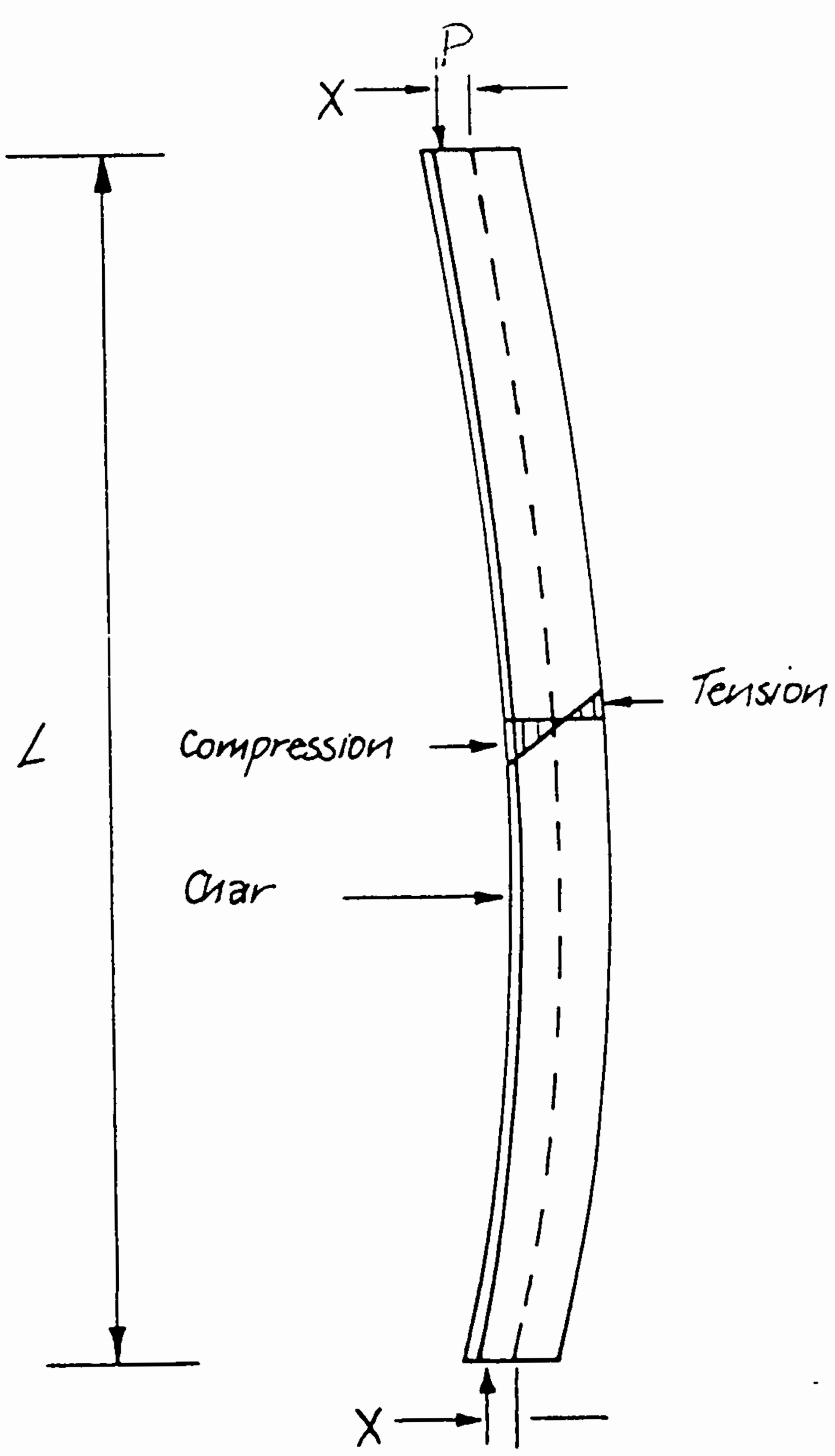
I = $\frac{(B-C)(D-C)^3}{12}$

E = modulus of elasticity

L = height of stud

M = bending moment due to furnace pressure





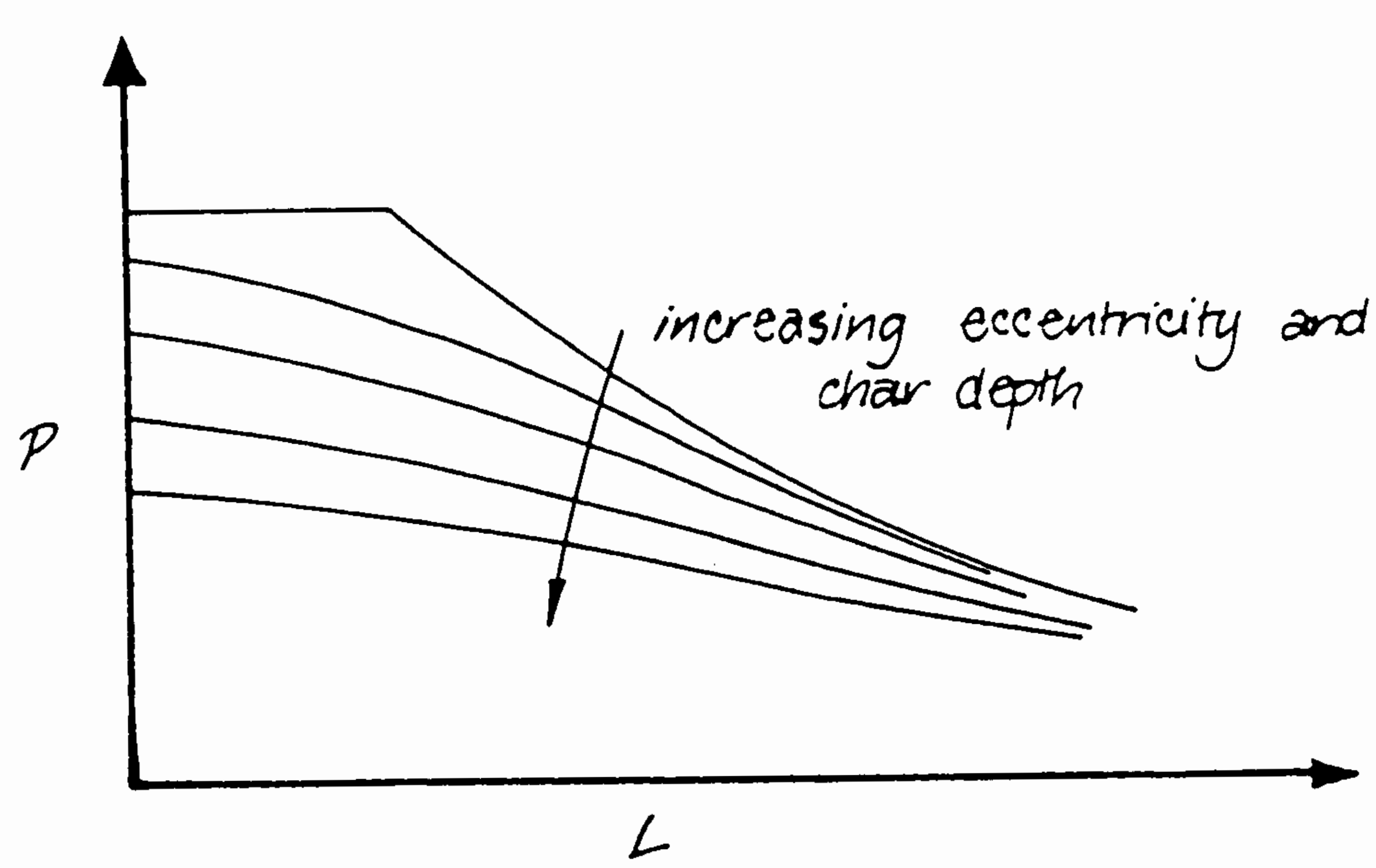


Figure 1: Charring of Studs

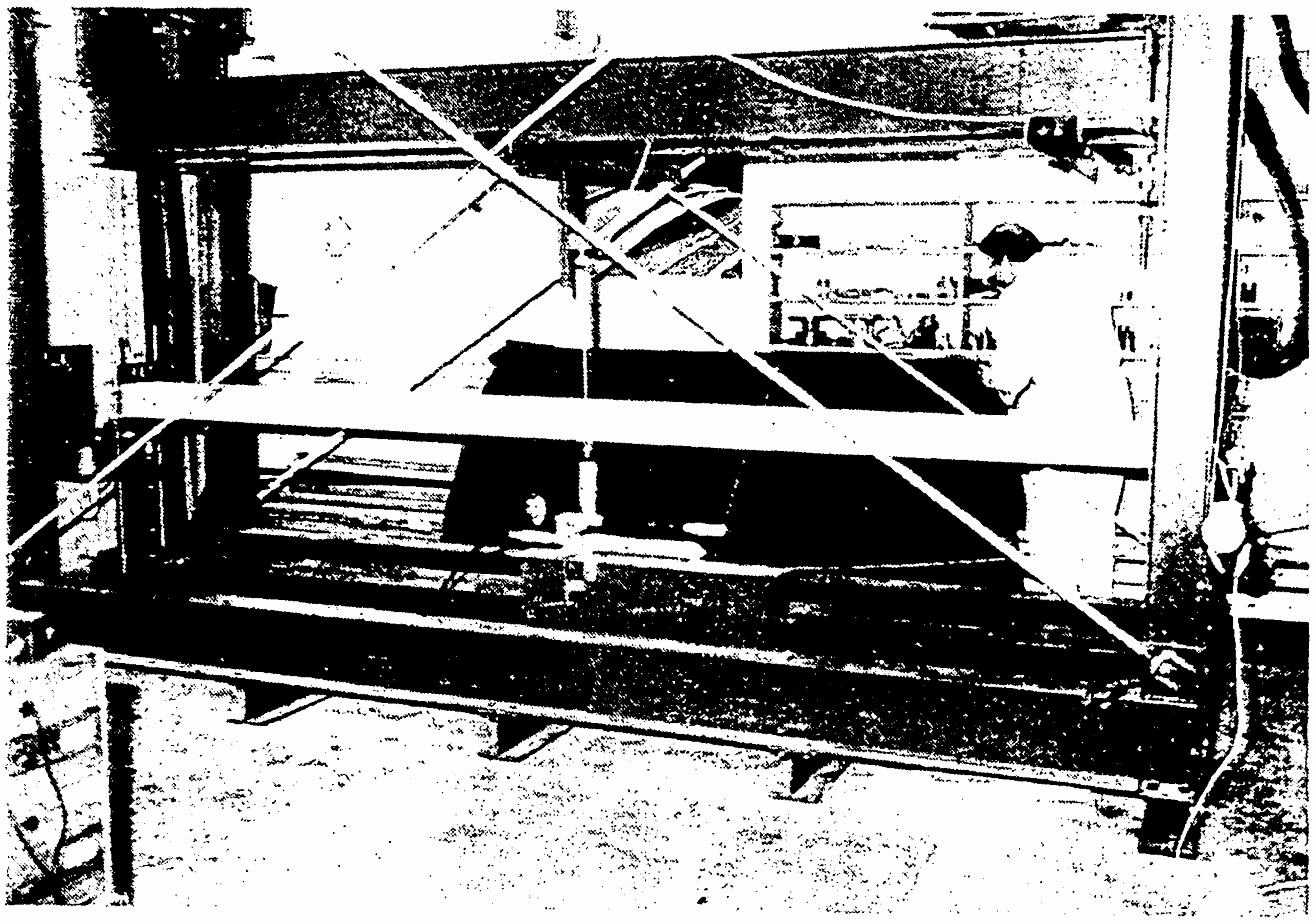


Figure 2: Measuring Modulus of Elasticity (E) as a Plank

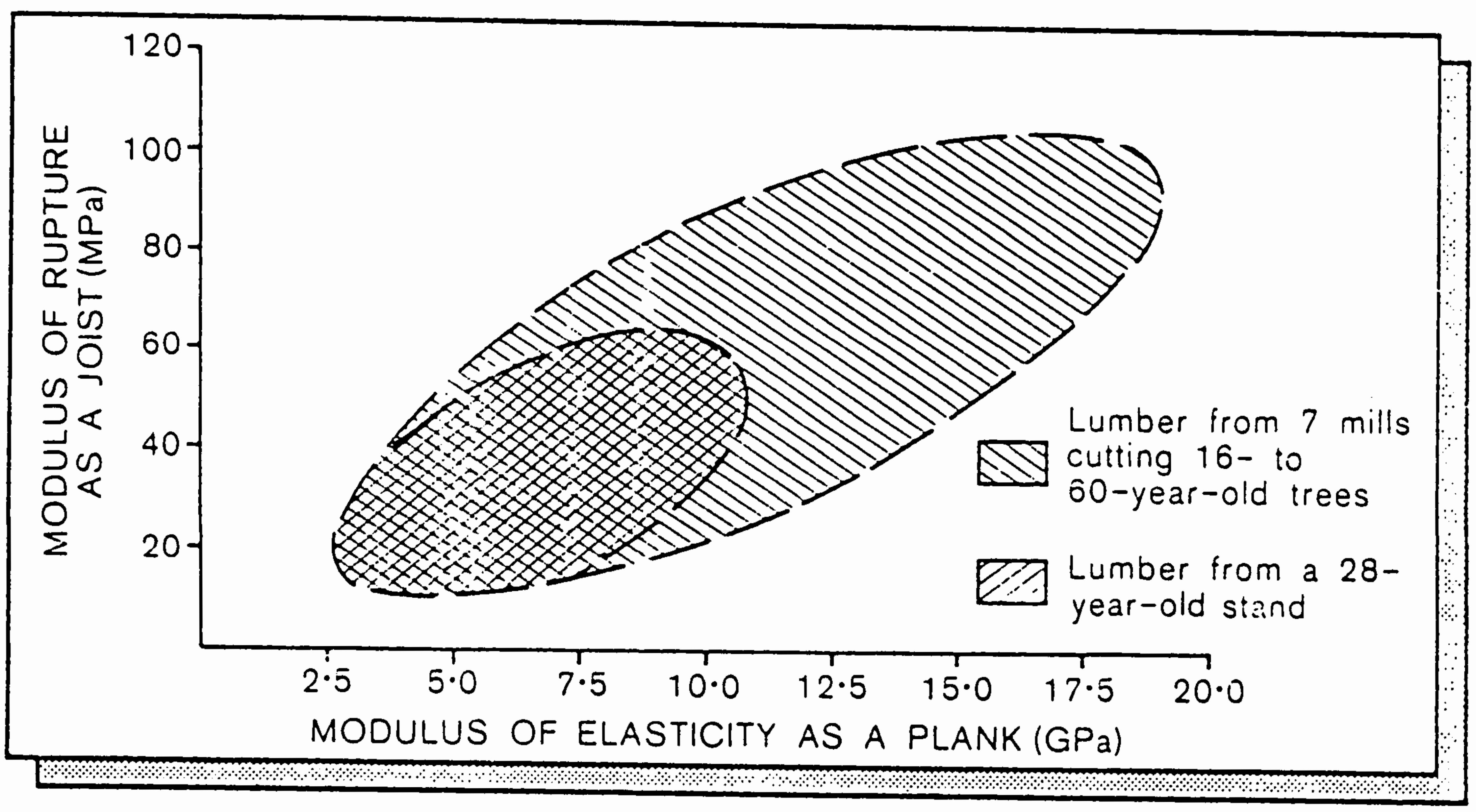


Figure 3: Relationship between Modulus of Rupture and Modulus of Elasticity

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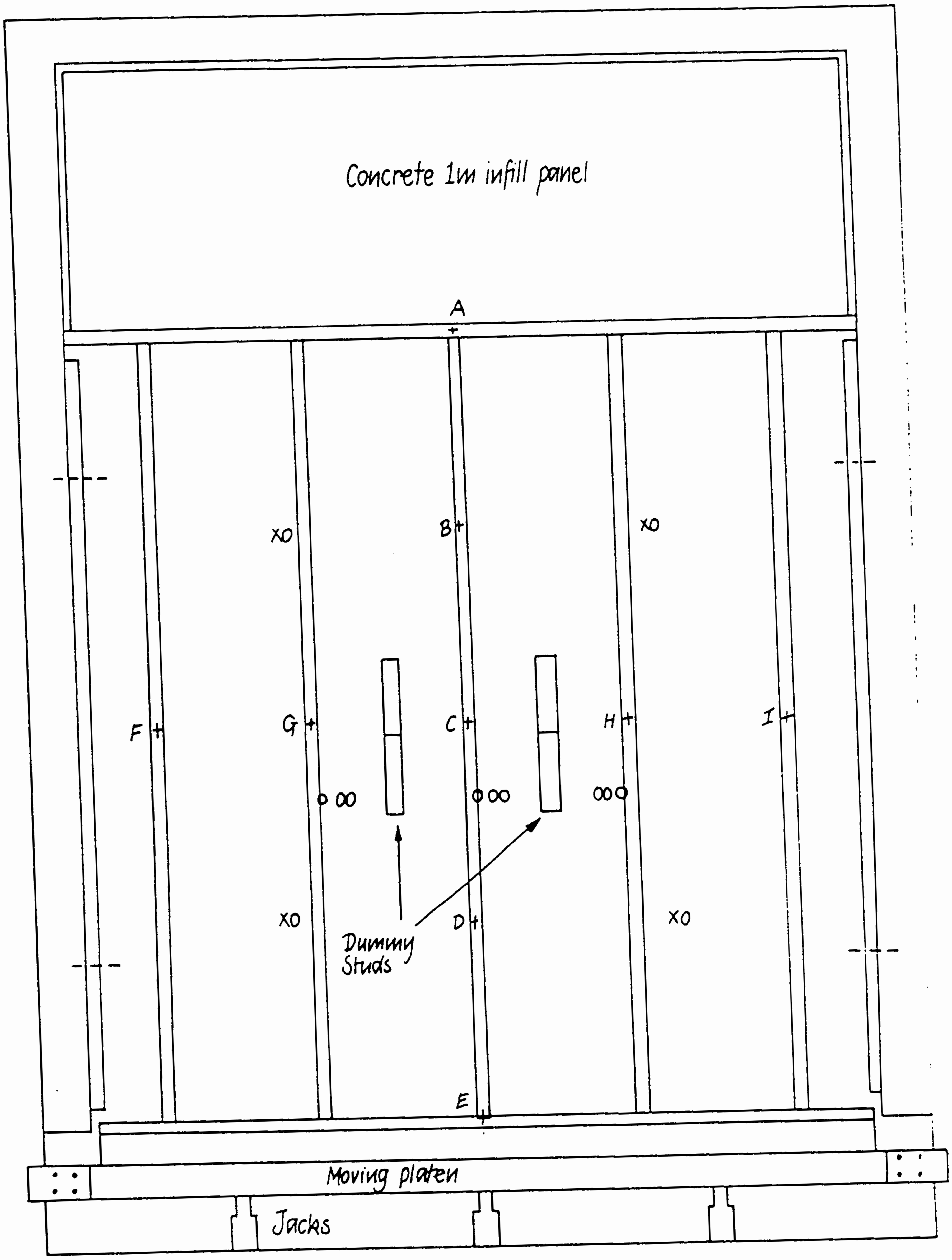


Notes:

1. Edge studs non load-bearing. 50mm gap top and bottom to plates. Bolts to frame finger tight only through slotted holes.
2. Kao wool packing between frame and top and bottom plates and edge studs.
3. Wall 3m wide and 3m high, except test #5 which was 4m high.
4. Thermocouple legend: x disc thermocouples on non-exposed side of non-exposed lining.
   o " " " non-exposed side of exposed lining
   - sheath thermocouples in dummy studs.
5. Nogs, where included, were at 800mm centres.
6. Deflection points A to I marked +.

Figure 4: Typical Test Specimen

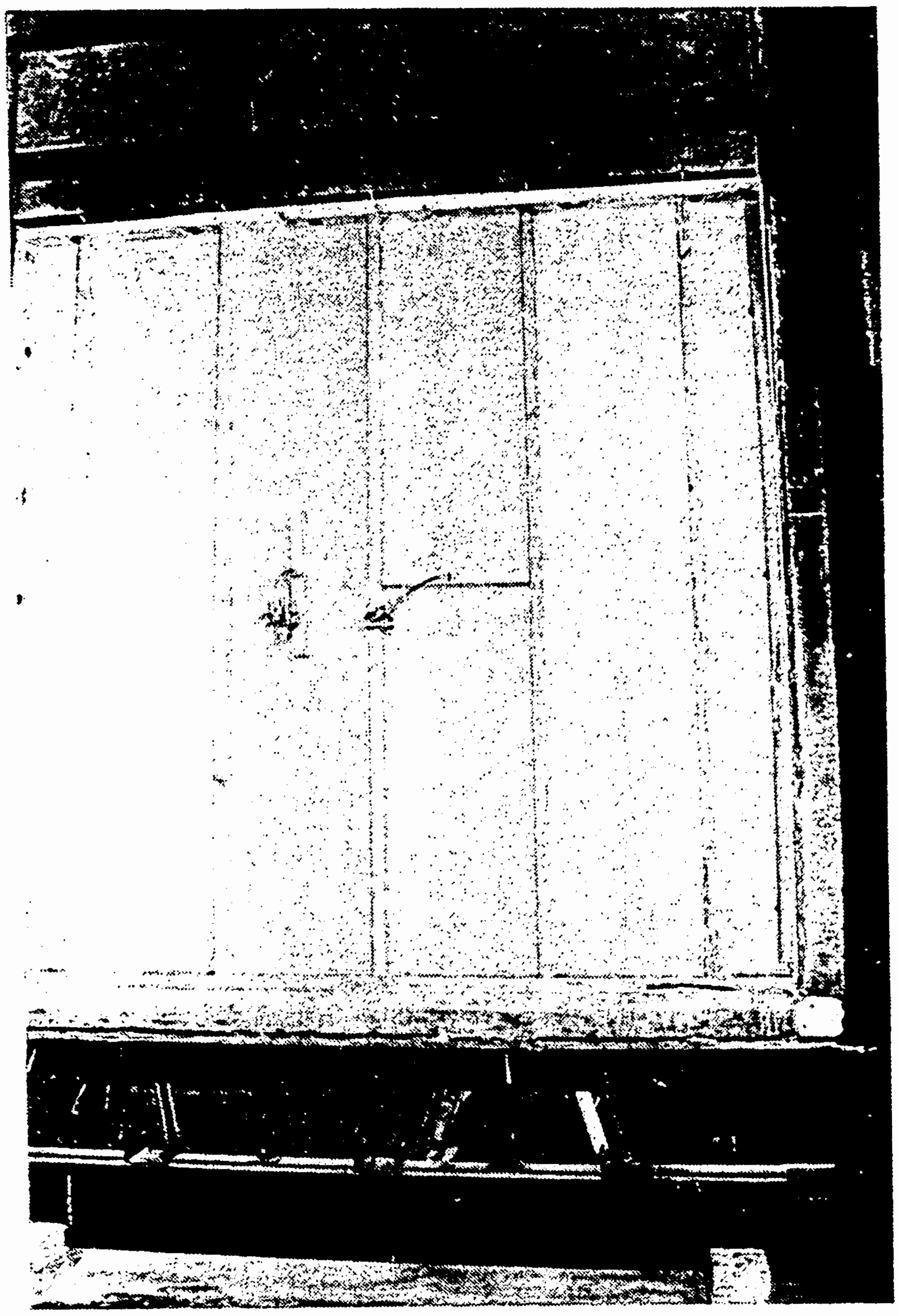


Figure 5: Typical Test Specimen Under Construction

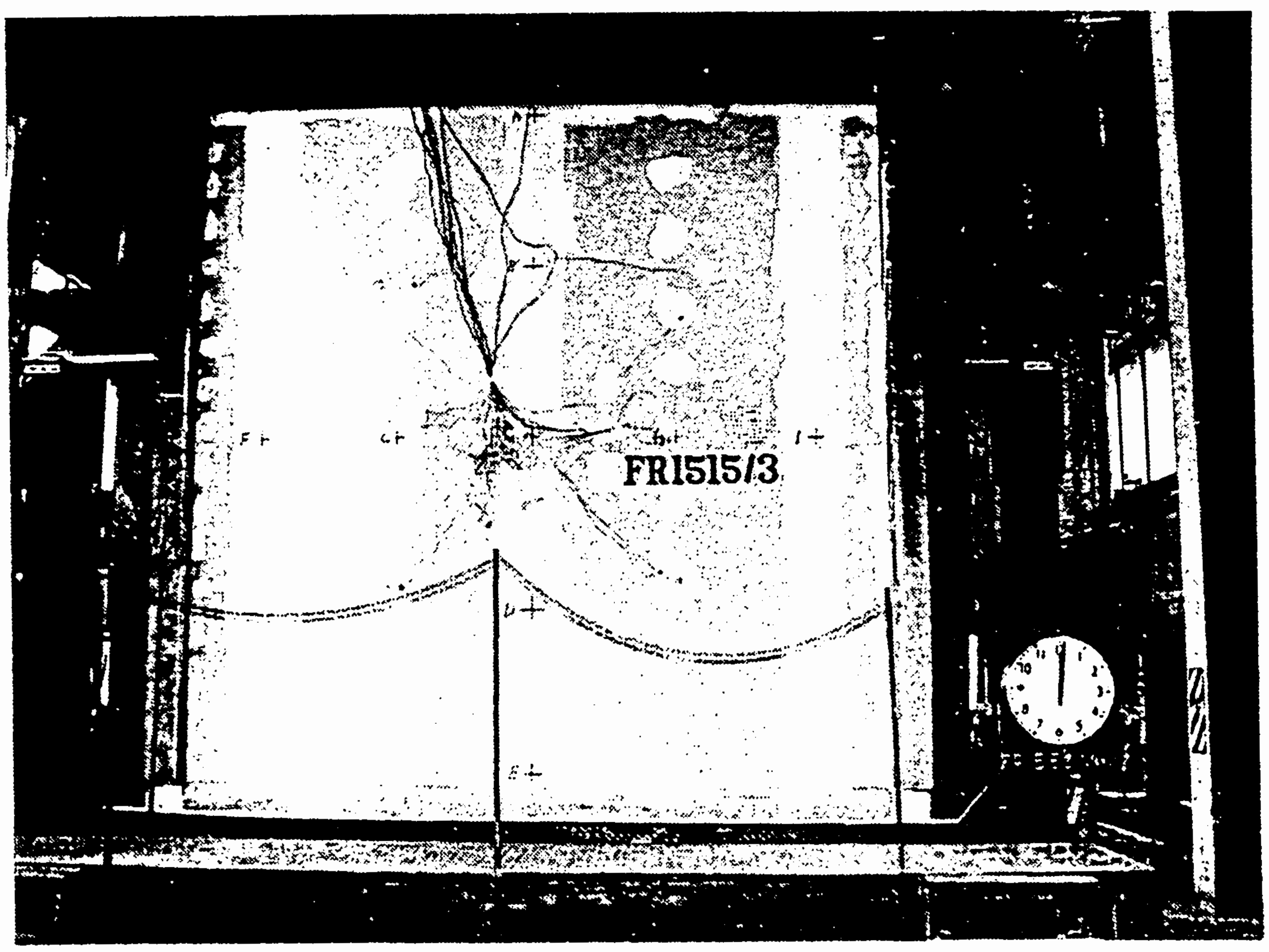


Figure 6: Typical Wall at Test Start

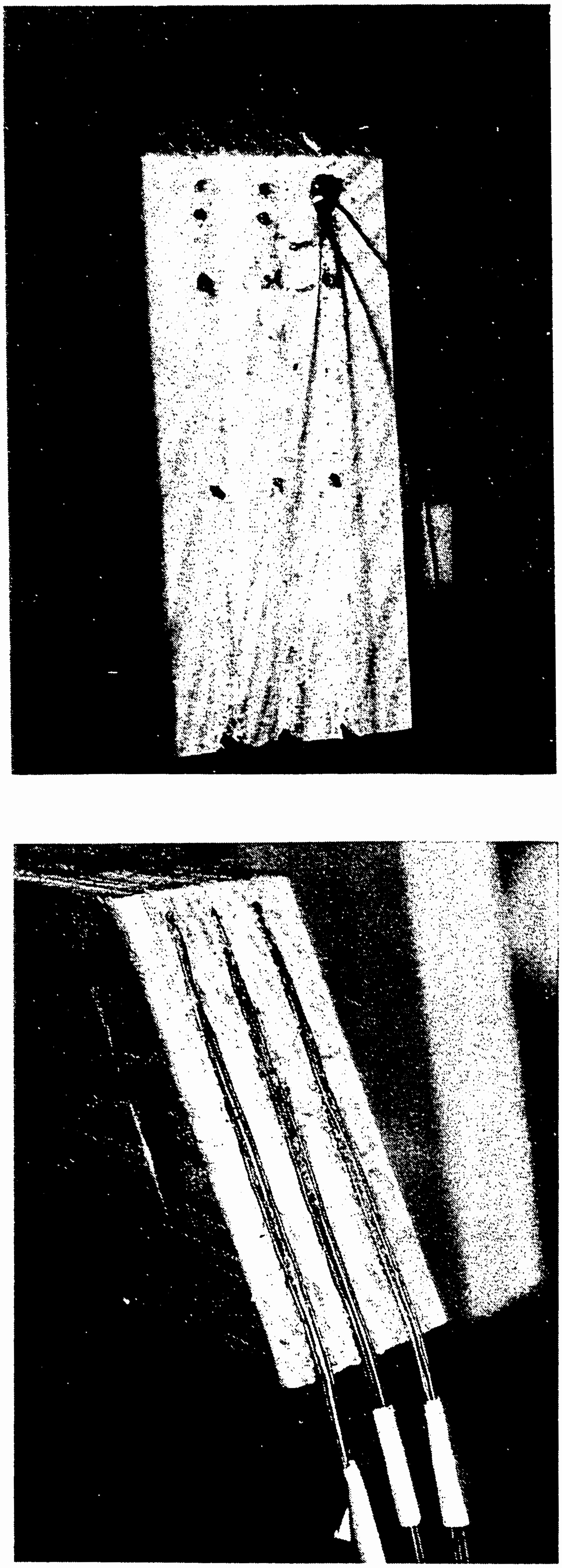
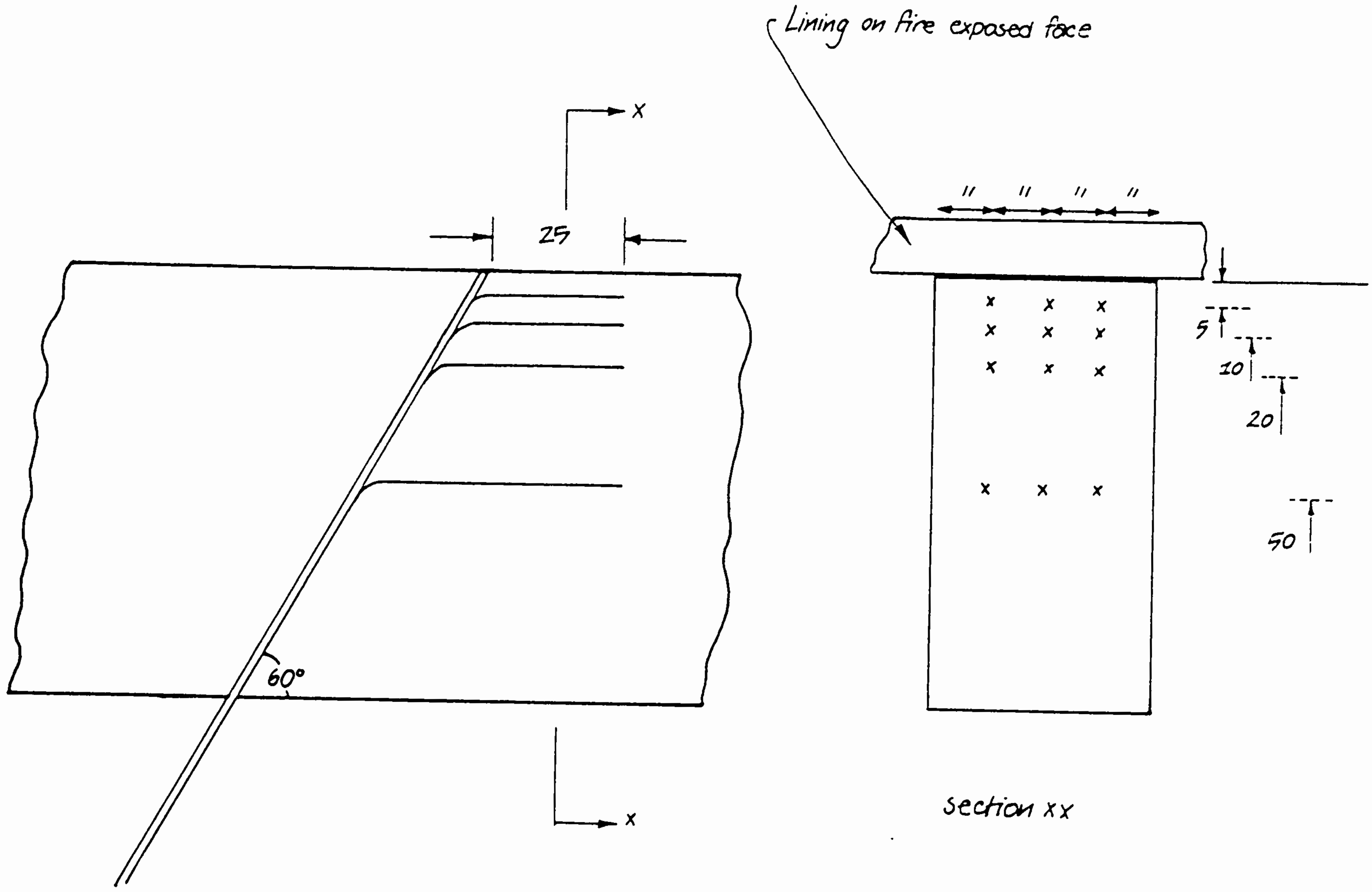


Figure 7: Instrumented Dummy Stud



12 sheath thermocouples marked "X" were embedded into a sectioned stud (dummy) as shown at the depths indicated and the stud was then glued back together and installed in wall as shown in figure 3.

Figure 8: Instrumentation of Dummy Studs

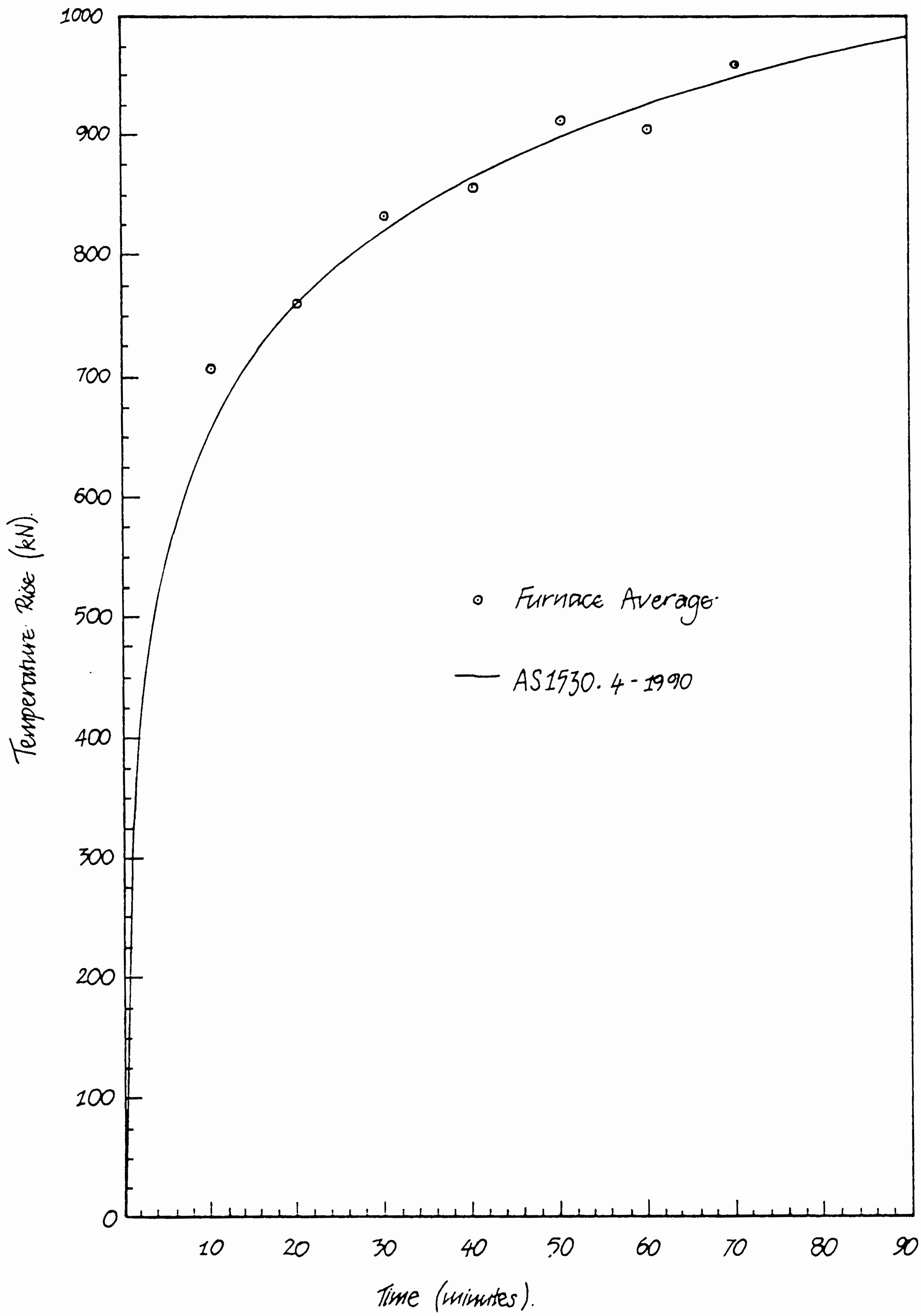


Figure 9: Furnace Temperatures

(initial temperature 15°C)

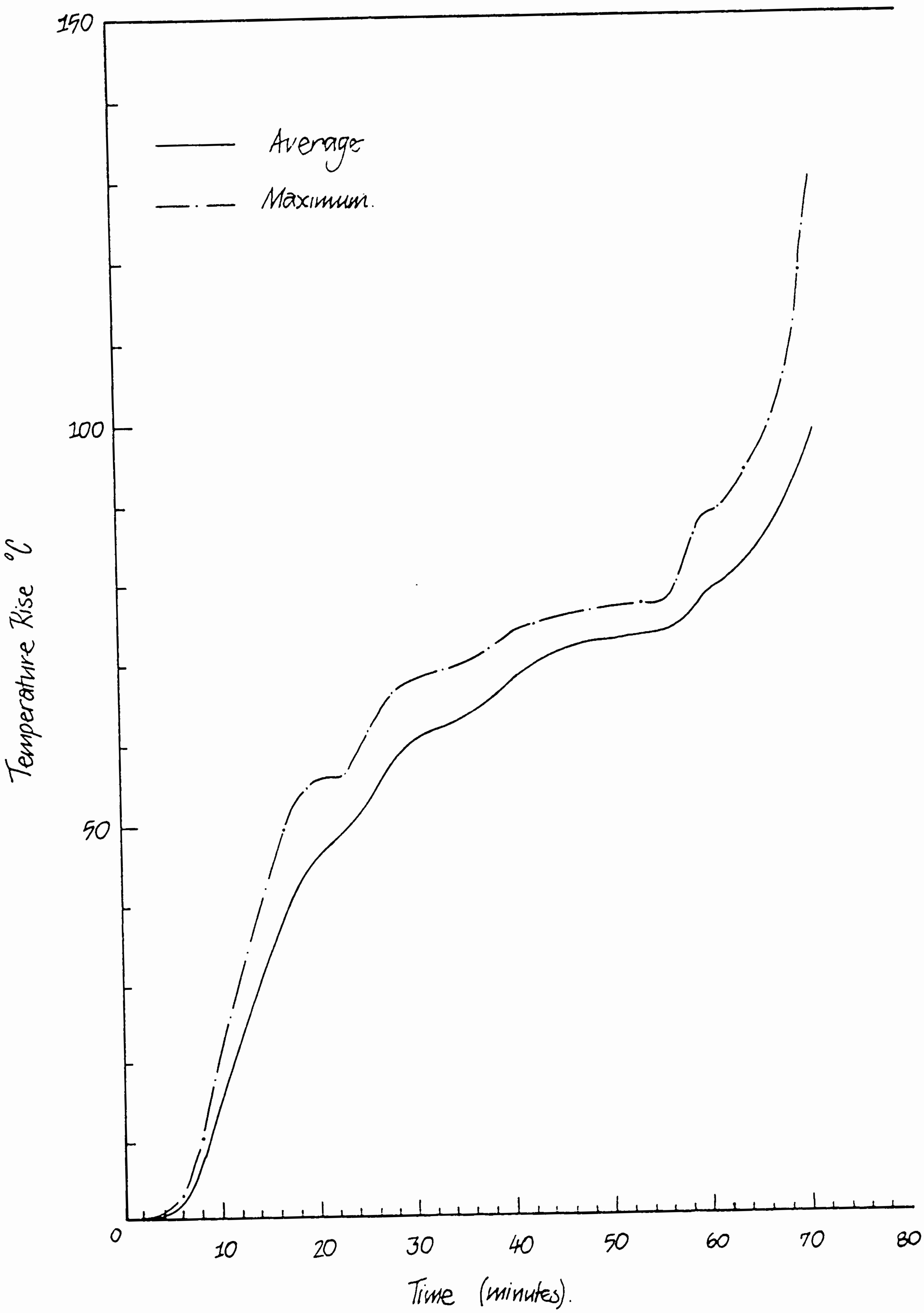


Figure 10: Typical Temperature Rise of Non-Exposed Face of Non-Exposed Plasterboard Lining, Insulation Criterion of Failure

(initial temperature 15°C)

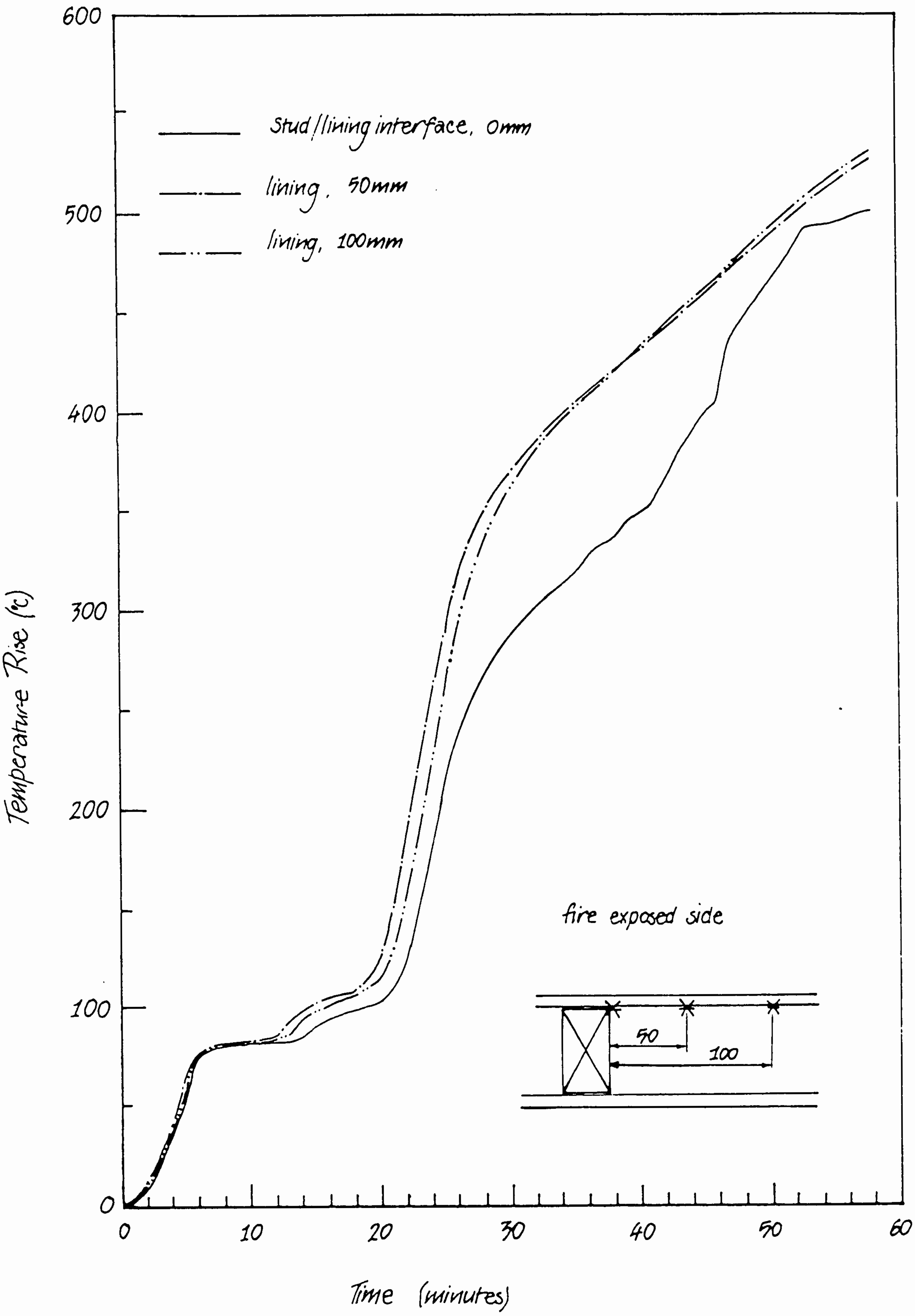


Figure 11: Typical Temperature Rise of Exposed Plasterboard Lining (non-exposed face)

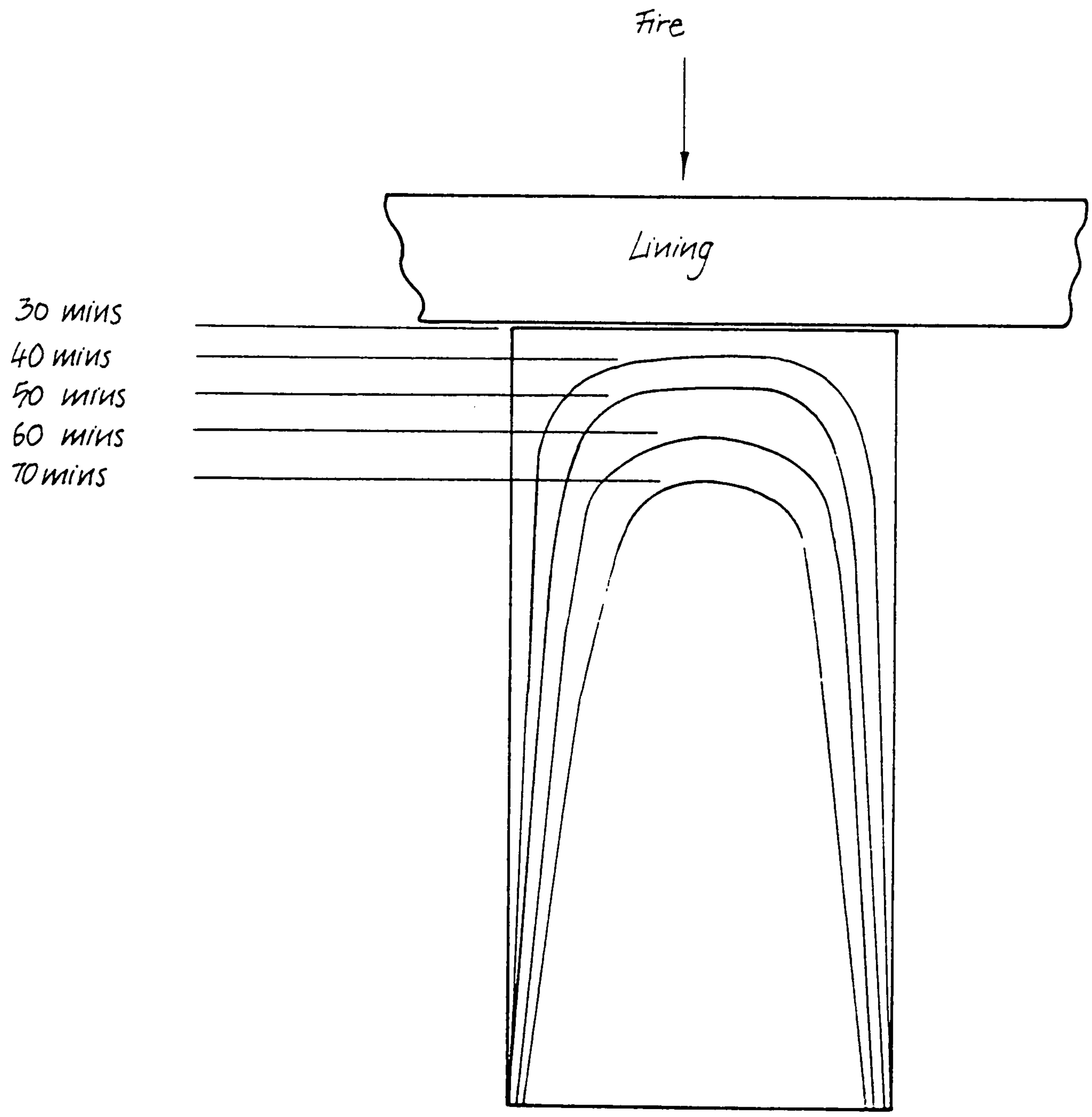


Figure 12: Typical Char Profiles at 10 Minute Intervals on a 100 x 50 Stud

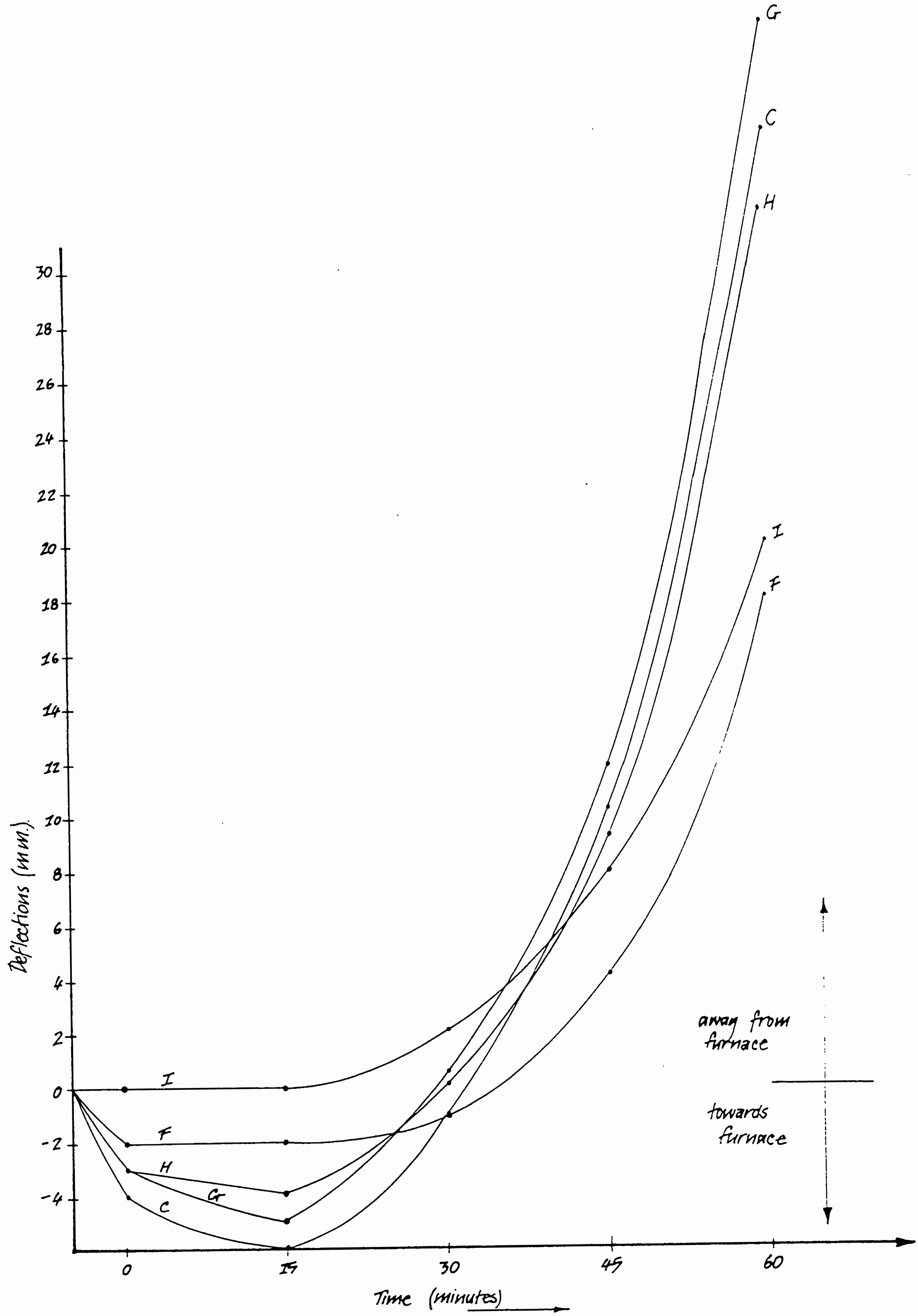


Figure 13: Typical Deflections at Stud Mid Height

Figure 14: Opening of Furnace at End of Test

Figure 15: Remains of Specimen at End of Test After Fire Extinguished

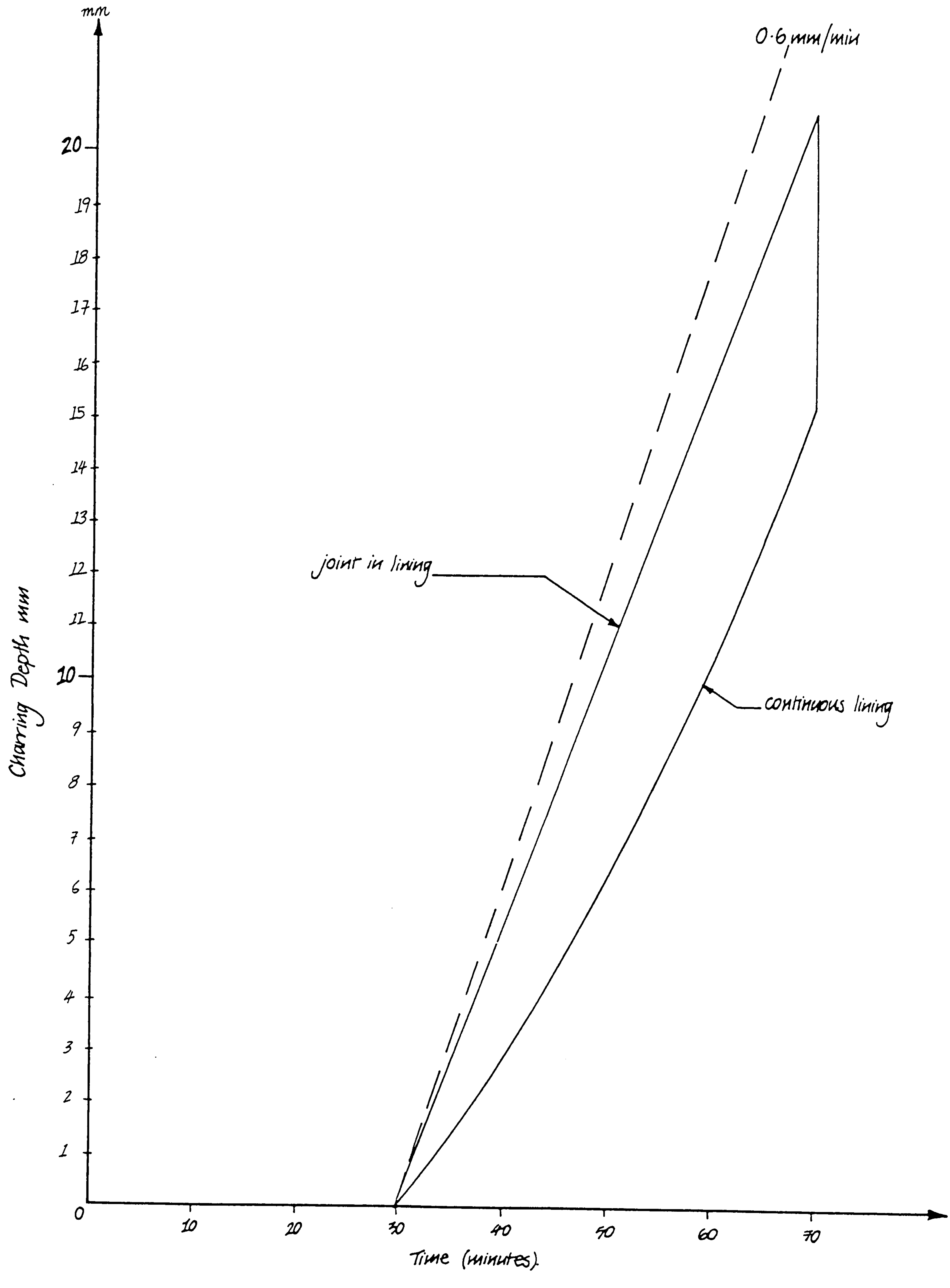


Figure 16: Char depth versus time

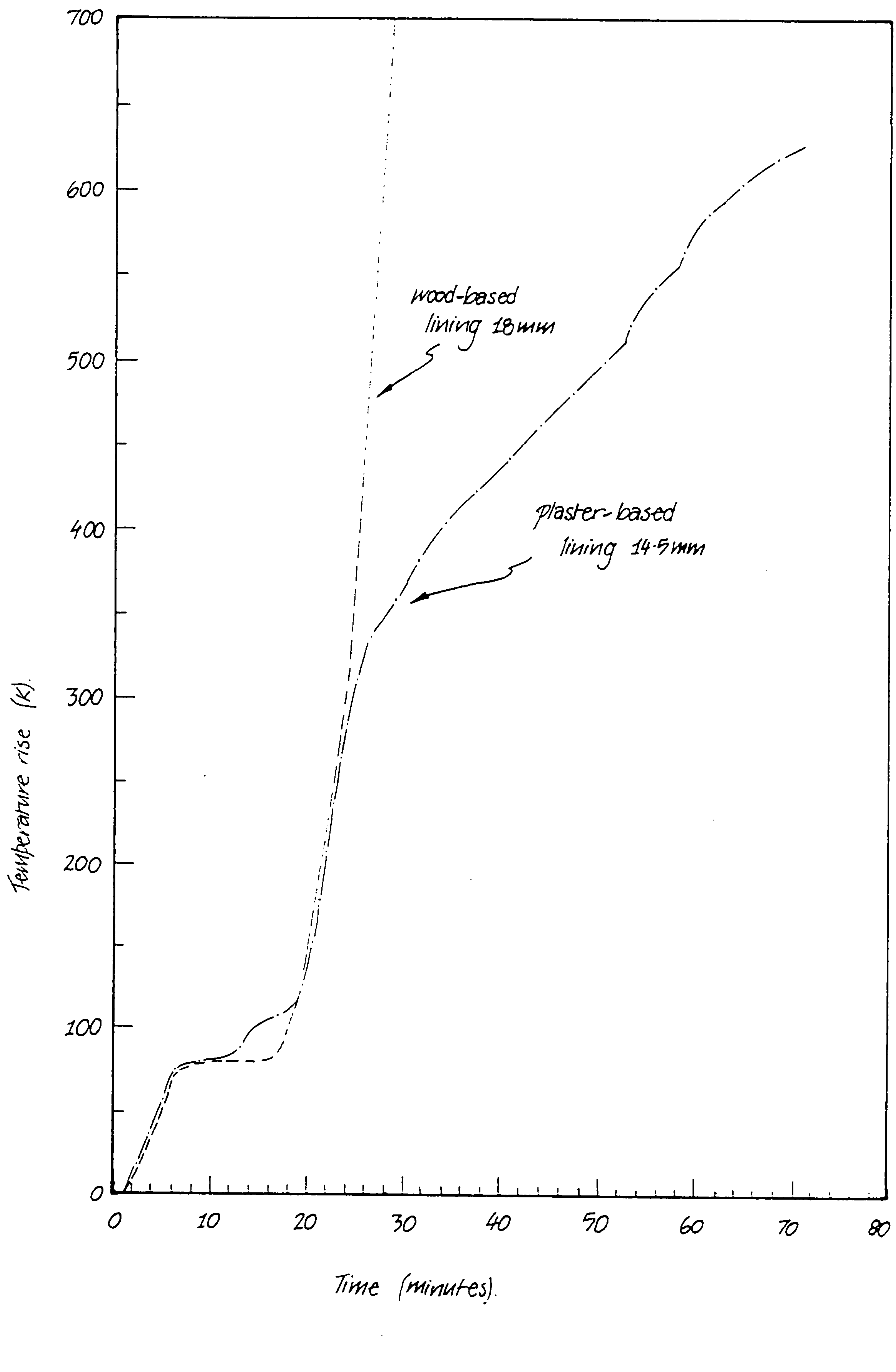


Figure 17: Typical Temperature Rise of Un-Exposed Face of Exposed Lining, for Plaster-Based Linings and Wood-Based Linings

(initial temperature 15°C)

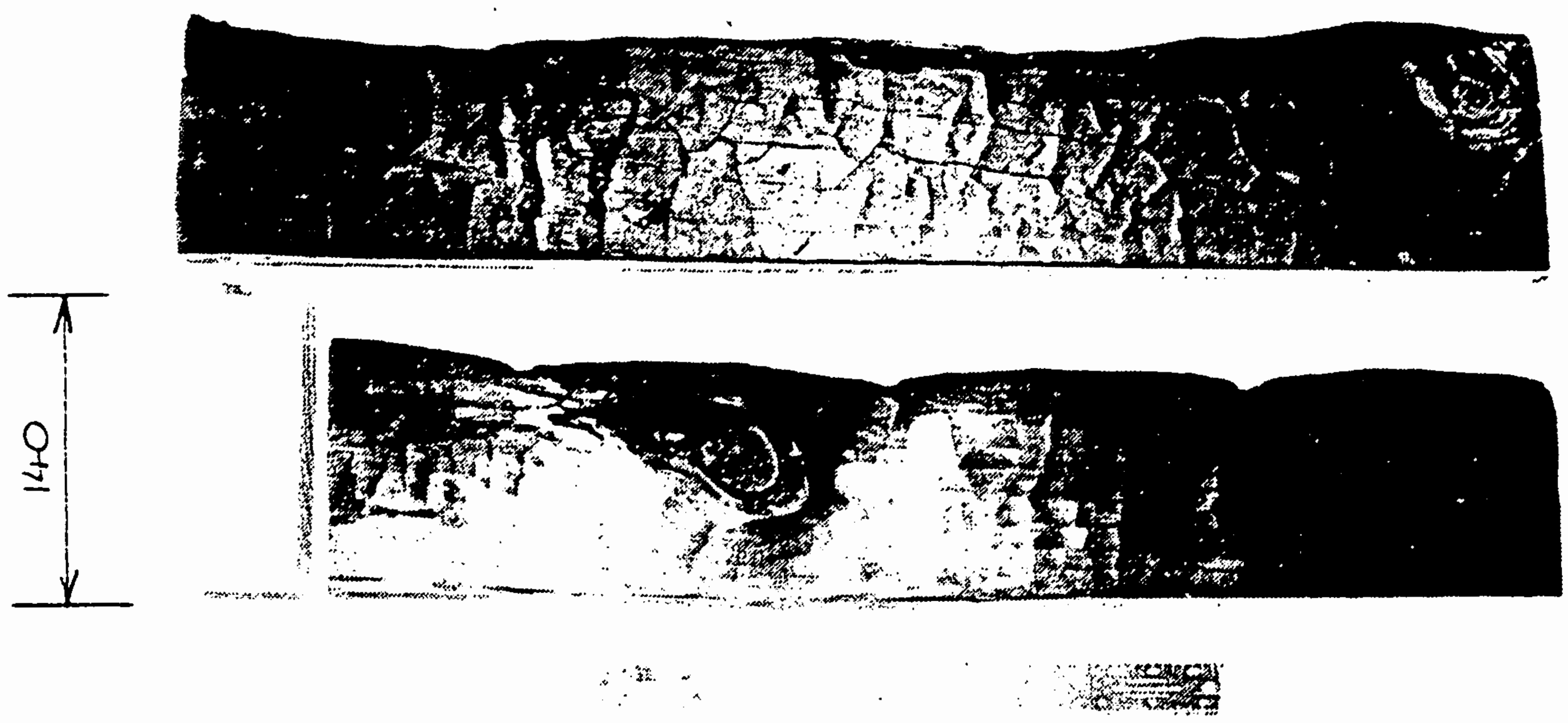


Figure 18: Sections of Studs From Test # 5

(150 x 50 nominal)
- top section continuous lining on exposed side
- bottom section joint in lining on exposed side

Note the influence of the nails and the knots on the charring rate

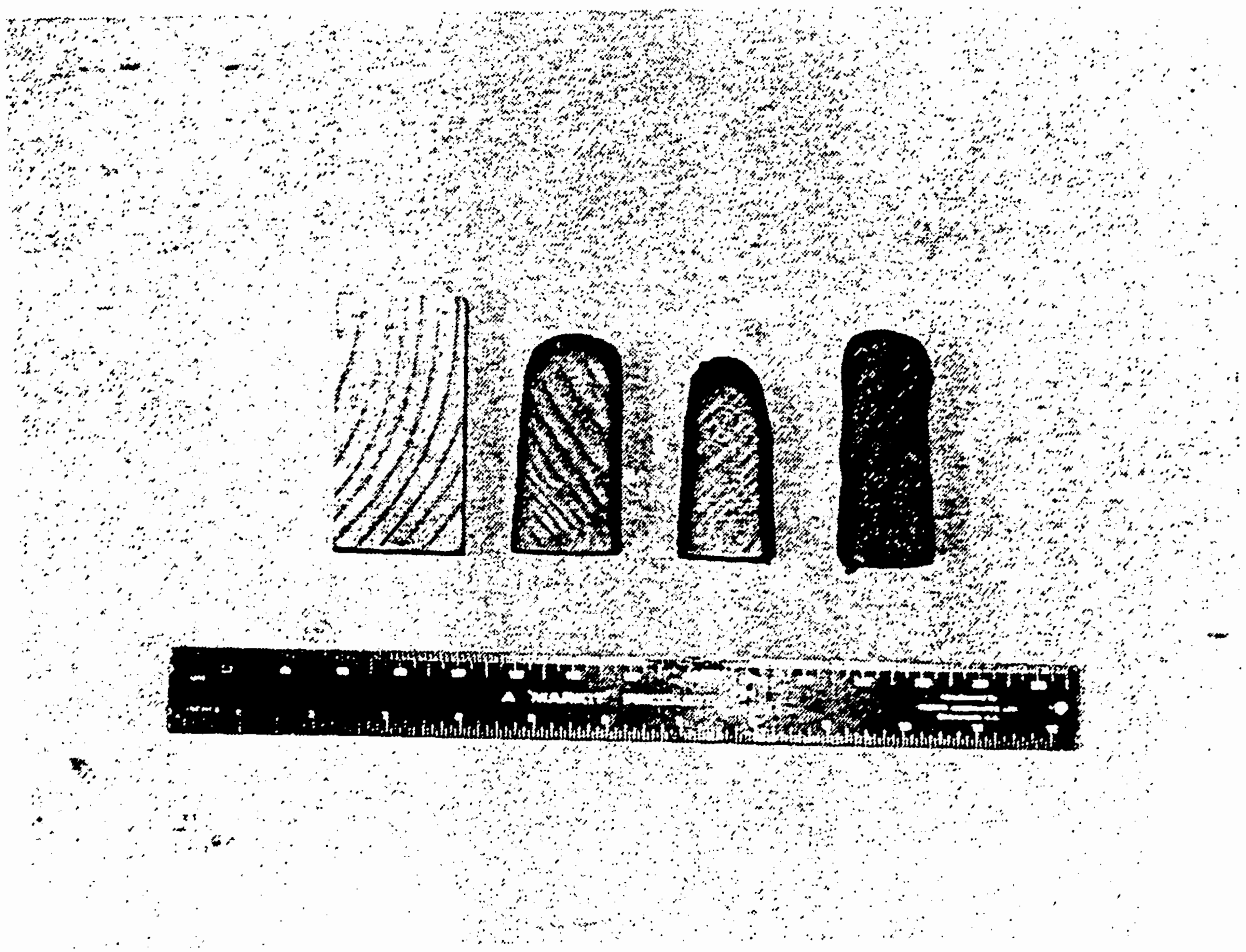


Figure 19: Stud cross-sections, left to right

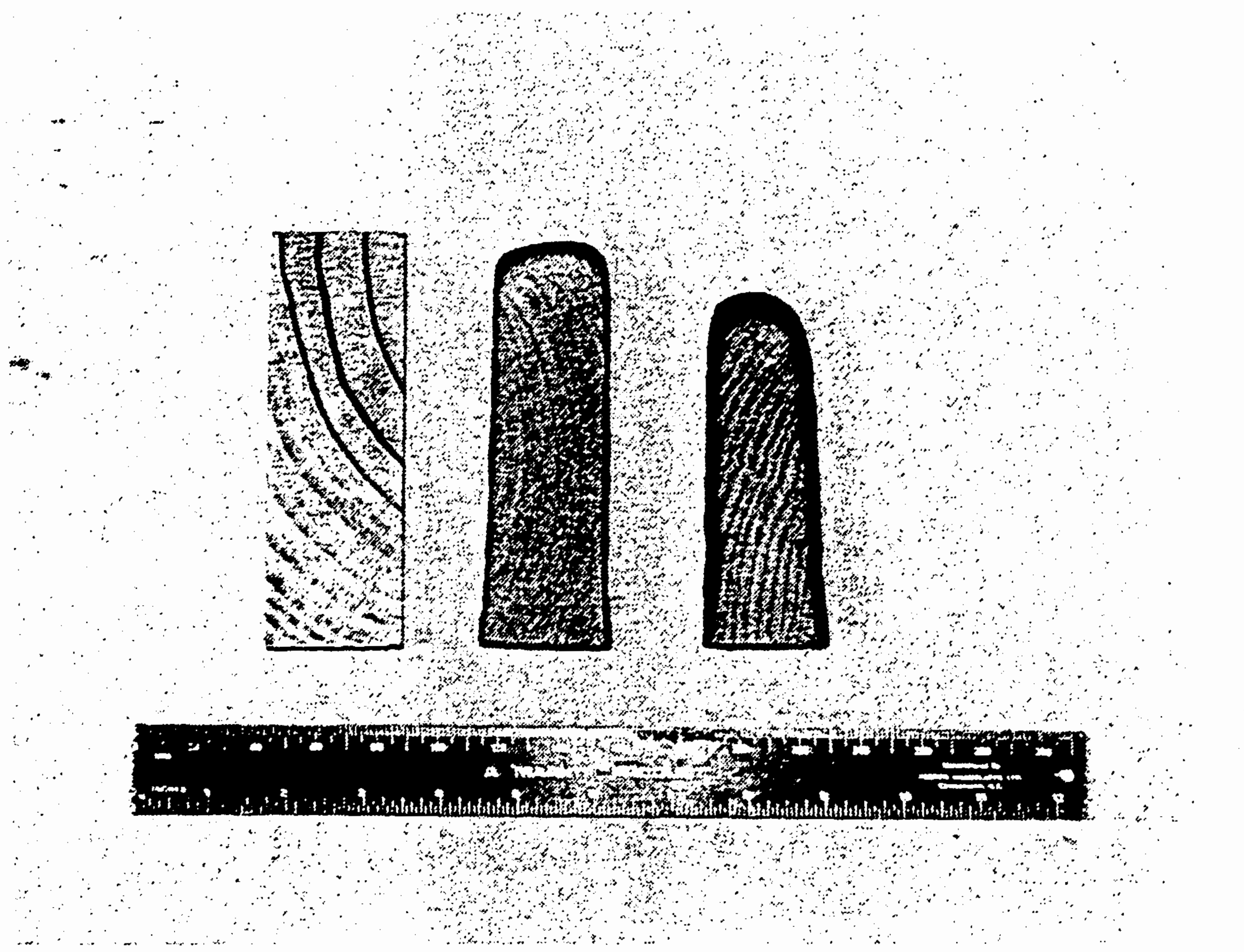


Figure 20: Stud cross-sections, left to right

Figure 21: Compressive A Failure Mode of Stud, in this Case at a Nail Location

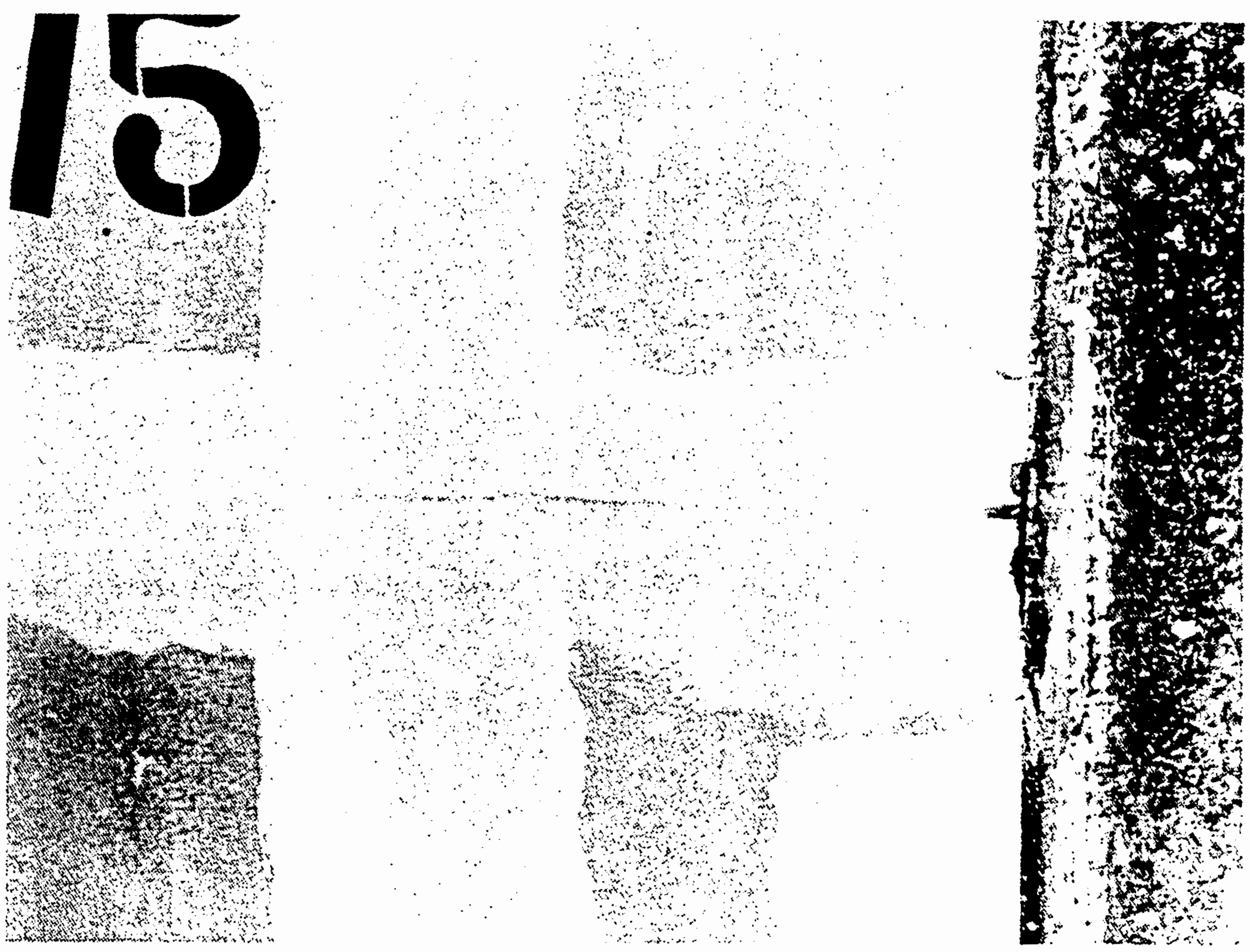


Figure 22: Compression of Horizontal Lining Joint on Wall Edge Near End of Test

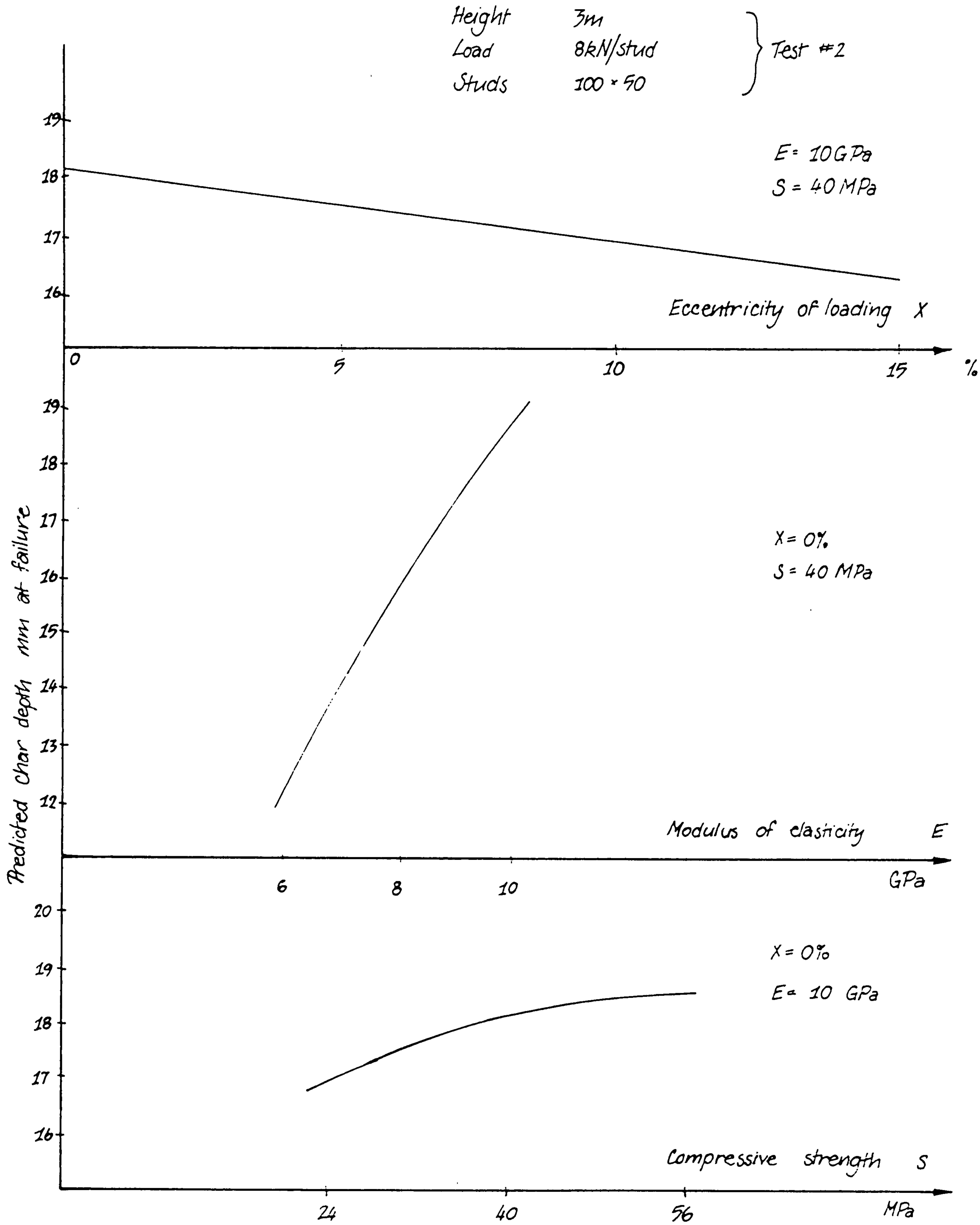


Figure 23: Relative Effects of Variations in Timber Properties

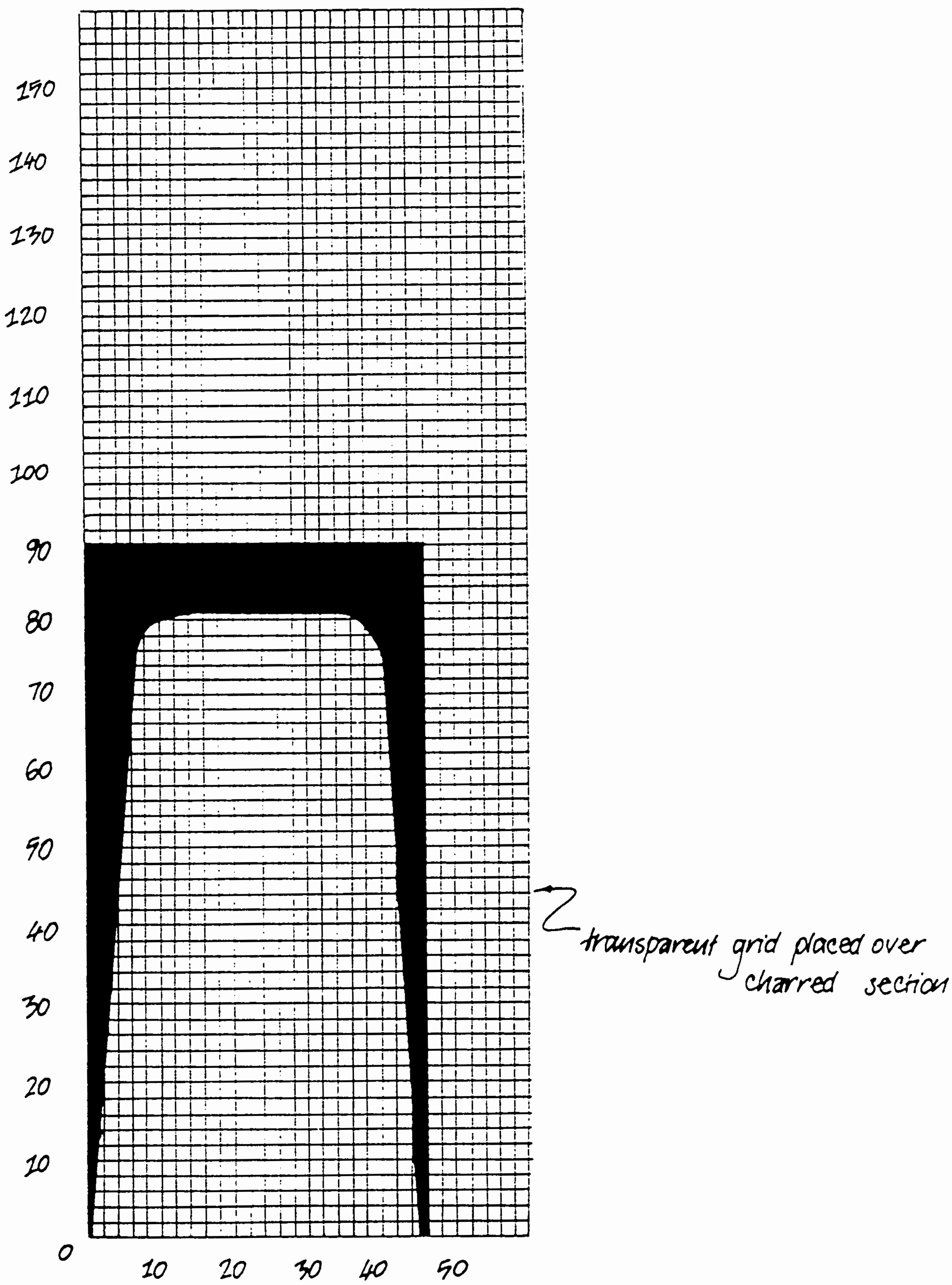


Figure 24: Method of Calculating A, I, C for Residual Stud Cross-Section

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