Fire Research Note No. 671

FIRE RESISTANCE OF LAMINATED TIMBER COLUMNS

by

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FIRE
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MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

Timber, one of the oldest structural materials, was used extensively in the construction of buildings before the development of other materials such as concrete and steel. Due to its combustible nature there have been frequent doubts concerning its performance in case of fire but experience has shown that large size timber sections are capable of giving a good performance. Conflagrations such as the Great Fire of London led to restrictions being placed on its free use but recently a more enlightened attitude is being taken. Despite its combustibility its use in buildings of certain types, particularly those intended for domestic occupancies, is permitted provided the design of the elements enables a specified degree of fire resistance to be obtained.

Over the last twenty years investigations have been undertaken on the fire resistance of timber elements, with the major emphasis on floors, beams and walls. Very little work appears to have been carried out on columns, with the exception of a few tests on solid sections 300 mm square by the Underwriter's Laboratories in U.S.A.[1]. Test data[2] are also available on beams and floors for domestic purposes from investigations undertaken at Boreham Wood.

One of the reasons for the lack of interest for a systematic study on timber elements, particularly columns, may have been the difficulty of obtaining sections without flaws, such as knots, shakes etc. and being able to specify their structural properties closely. Recently developed techniques of laminating sections, commonly termed 'glue-lam', have enabled larger sections of specified properties to be produced by permitting the use of selected grades of the material.

Tests have been carried out by laboratories in Scandinavia[3] and Germany[4] on the performance of laminated beams which have indicated that the material is capable of giving a good performance under fire conditions. Laminated columns did not receive much attention in the course of these investigations; a few tests in France[5] indicated that, when suitably designed, their fire resistance was similar to that expected from solid sections.

As a result of discussions between the Joint Fire Research Organization and the Timber Research and Development Association (TRADA) a co-operative research programme on the fire resistance of laminated timber columns was formulated. In addition to providing basic data on the performance of columns, it was expected that information would be available for inclusion in the British Standard Code of Practice No. 112[6], which at present does not provide any data on the fire resistance of timber structures.

OUTLINE OF PROGRAMME

The factors which could influence the performance of timber columns were examined and the following were considered to be necessary for inclusion in the programme.

1. Species of wood
2. Type of glue
3. Shape of the section
4. Test load
5. Quality of wood
6. Size of the section
7. Fire retardant treatments
8. Encasement by a non-combustible material

The first four were considered to be more important than the others and these were to be dealt with by a statistically planned experiment. On the remainder, data was to be obtained by check tests without a statistical plan.

The fire tests on columns were to be performed until the specimens failed so as to obtain full information on the influence of various factors. However, to comply with the requirements of the British Standard[7] relating to loadbearing elements it was necessary to have information on the residual strength of laminated columns after heating for a predetermined period. For this purpose a few additional tests were performed as a separate part.

Before the design of the various specimens was undertaken, two preliminary experiments were performed on 230 mm square columns of Douglas Fir. In these tests a fire resistance of 35 to 75 minutes was obtained depending upon the test load. On the basis of these tests a 230 mm square column was taken to be the standard size when dealing with factors other than size and shape and a load equal to 50 per cent of that permissible was adopted as the Standard test load when load was not the factor under examination. Under these conditions the fire resistance was likely to be neither too short to mask the influence of various factors nor too long to make the tests unnecessarily lengthy.

PART 1 - PRIMARY PROGRAMME

In the primary programme the species of wood and the types of glue to be investigated were discussed with the Timber Research and Development Association and the choice was made on the basis of using materials commonly available and representing a range of performances. Four common species of soft wood, used for structural work were selected and four different types of glue were employed in the manufacture of the specimens.

To determine the effect of section, two rectangular profiles were used which by a judicious choice possessed the same structural properties and had cross-sectional areas similar to the 230 mm square basic section selected. All specimens were fabricated from 19 mm thick laminates and utilized 75 per cent grade material except when investigating the effect of quality. The fabrication of specimens was undertaken at the laboratories of the Timber Research and Development Association in a special compression machine.

The maximum permissible load for the specimens was computed according to the specification in CP 112, assuming fixed end conditions; the detailed calculations are given in Appendix I.

Each specimen was given a reference code, the first letter representing the species of wood, the second the type of glue, followed by the serial number.

The following range of factors was examined in the primary programme, with the reference letters given in brackets.

1. Species of wood: Douglas fir (F) - Pseudotsuga taxifolia
   European redwood (R) - Pinus silvestris
   Western hemlock (H) - Tsuga heterophyla
   Western red cedar (C) - Thuja plicata
2. Types of glue: Resorcinol (R) - phenol resorcinol formaldehyde
   Phenolic (P) - phenolic resin
   Urea (U) - urea formaldehyde
   Casein (C) - casein
3. Shapes: 230 mm x 230 mm (breadth/depth $\left(\frac{b}{d}\right) = 1$)
   305 mm x 175 mm $\left(\frac{b}{d} = 1.74\right)$ and 380 mm x 140 mm $\left(\frac{b}{d} = 2.71\right)$
4. Test loads: Full design, 50 per cent design and 25 per cent design loads.

The statistical programme of 16 tests was devised as a Graeco-Latin Square, with partial replication to increase precision on certain effects, and is shown in Table 1, below.

TABLE 1. Experimental design

	Douglas Fir	Western Hemlock	Redwood	Western Red Cedar
Urea	Y α	Z α	Y δ	X β
Casein	Y β	X δ	Y α	Z α
Resorcinol	Z δ	Y β	X α	Y α
Phenolic	X α	Y α	Z β	Y δ

Load

X = 100 per cent design load

Y = 50 per cent design load

Z = 25 per cent design load

Shape

α = 230 mm x 230 mm

β = 305 mm x 175 mm

δ = 380 mm x 140 mm

The details of the specimens used in this part of the investigation are given in Table 2

Table 2 - Details of specimens for the statistical programme

Column Number / Factors	F U 1	F C 2	F R 3	F P 4	H U 5	H C 6	H R 7	H P 8	R U 9	R C 10	R R 11	R P 12	C U 13	C C 14	C R 15	C P 16
Species																
Douglas Fir	x	x	x	x												
Western Hemlock					x	x	x	x								
Redwood									x	x	x	x				
Western Red Cedar													x	x	x	x
Glue																
Urea	x				x				x				x			
Casein		x				x				x				x		
Resorcinol			x				x				x				x	
Phenolic				x				x				x				x
Shape																
- 230 mm x 230 mm	x			x	x			x		x	x			x	x	
- 305 mm x 175 mm		x					x					x	x			
- 380 mm x 140 mm			x			x			x							x
Test load																
X - Design				x		x					x		x			
Y - 50 per cent design	x	x					x	x	x	x					x	x
Z - 25 per cent design			x		x							x		x		

PART 2 - PROGRAMME FOR ADDITIONAL FACTORS

In this part of the programme the following factors were examined and except when investigating the effect of size, the specimens were 230 mm square.

1. Quality of wood: 90, 75, 65 and 50 per cent grade laminates
2. Size of section: 150 mm x 150 mm, 230 mm x 230 mm, 300 mm x 300 mm and 380 mm x 380 mm
3. Treatment of wood: Two types of impregnation treatment (Types P and O) and one type of surface coating (Type A)
4. Effect of encasement: A 13-mm encasement of asbestos insulation board.

No attempt was made to use identical types of wood and glue for this part of the programme; specimens were manufactured at random, utilizing the wood and the glue available.

The arrangement of specimens for this part of the programme is shown in Table 3.

PART 3 - RESIDUAL STRENGTH

The British Standard Test[7] for fire resistance requires that loadbearing members should not collapse during the heating period and should be capable of withstanding a re-application of the test load after a lapse of 48 hours. This requirement was considered to be restrictive for an investigation of this nature and therefore the tests were continued until collapse occurred in order to obtain information on the maximum influence of different factors.

However, to obtain data for the purpose of grading where necessary, three additional tests were performed on 230 mm square specimens, detailed in Table 3 in which the heating was terminated prior to the collapse. In one case the load was immediately increased to measure the residual strength; the others were reloaded after a lapse of 48 hours.

TESTING TECHNIQUE

After manufacture, the specimens were finished to size on a planing machine at the laboratories of TRADA and cut to a length of 3.1 m before delivery to the Fire Research Station.

Table 3 - Details of specimens for programmes for additional factors and residual strengths

Factors \ Column Number	R C 17	R C 18	R C 19	H P 20	H P 21	H P 22	F U 23	F U 24	F U 25	R R 26	F R 27	C C 28	C C 29
<u>Species</u>													
Douglas Fir							x	x	x		x		
Western Hemlock				x	x	x							
Redwood	x	x	x							x			
Western Red Cedar												x	x
<u>Glue</u>													
Urea							x	x	x				
Casein	x	x	x									x	x
Resorcinol										x	x		
Phenolic				x	x	x							
<u>Size</u>													
152 mm x 152 mm (6 in x 6 in)	x												
230 mm x 230 mm (9 in x 9 in)				x	x	x	x	x	x	x	x	x	x
300 mm x 300 mm(12 in x 12in)		x											
380 mm x 380 mm(15 in x 15in)			x										
<u>Quality</u>													
90 per cent grade				x									
65 per cent grade					x								
50 per cent grade						x							
<u>Residual strength</u>													
Period A - 45 min							x						
Period B - 45 min								x					
Period C - 60 min									x				
<u>Treatment and encasement</u>													
Impregnation 'P'										x			
Impregnation 'O'											x		
Surface coating 'A'												x	
Asbestos insulation board encasement													x

They were allowed to condition in the testing laboratory to an equilibrium moisture content of 10 - 12 per cent before being prepared for a fire test.

The specimens were mounted in a special concrete base, with the lower 150 mm embedded in a recess and grouted to provide fixity. At the top of the specimens a refractory concrete cap, 375 mm square was provided, having a 25 mm recess with a soft asbestos board on top to provide a bearing. The specimen, with its concrete base and cap, as shown in Figure 1 and Plate 1, was mounted in the loading frame of the column testing furnace, ensuring that it was vertical. Before the commencement of the test, the moisture conditions of the specimens were determined at a number of positions using a resistance type moisture meter.

In some of the specimens thermocouples were provided, sited in 1.5-mm holes drilled to different depths and after inserting the hot junctions the holes were plugged with asbestos. A continuous record of temperatures was taken during the test. In some cases the charring and disintegration of timber from the outer laminates affected the thermocouples and resulted in fluctuating temperature records.

The test load on the specimens was maintained constant during the test and measurements were also taken at intervals of its vertical movement; failure was deemed to have occurred when the specimen was no longer able to support the load. In addition to observing the behaviour of the specimens during the tests, photographs were also taken before and after the test to show the appearance of the specimen.

The heating conditions during the test followed the standard time/temperature relationship of B.S. 476 : Part 1 : 1953. At the end of the test the specimens were quenched with water, and when they could be handled, small pieces were cut from the central area to measure the extent of damage by charring.

TEST RESULTS

The temperature curves obtained from some typical specimens, are shown in Figures 2 - 4 and the appearance of a number of specimens before and after the test is shown in Plates 1 to 4.

PART 1. - STATISTICAL PROGRAMME FOR PRIMARY FACTORS

In Table 4 the fire resistance is given in minutes for the sixteen tests in this part of the programme. It was found necessary for statistical analysis to use logarithmic transformations; these are shown in brackets. The detailed statistical analysis of the results is given in Appendix 2.

Table 4. Fire resistance in minutes* with logarithmic transformations in brackets

Glue \ Species	Douglas fir	Western Hemlock	Redwood	Western Red Cedar
Urea	54.5 (1.7364)	73.0 (1.8633)	47.0 (1.6721)	34.5 (1.5378)
Casein	53.0 (1.7243)	23.0 (1.3617)	54.00 (1.7324)	61.5 (1.7889)
Resorcinol	74.25 (1.8707)	49.0 (1.6902)	44.5 (1.6484)	43.3 (1.6365)
Phenolic	45.0 (1.6532)	68.5 (1.8357)	75.5 (1.8779)	39.0 (1.5911)

*For all statistical calculations, fire resistance times were estimated to two decimal places.

PART 2 - PROGRAMME FOR ADDITIONAL FACTORS

The fire resistance in minutes of ten specimens to determine the influence of additional factors is given in Table 5.

Table 5. Fire resistance in minutes of ten specimens to determine the effect of additional factors

Additional factor	Column No.	Fire resistance min
Quality		
90 per cent grade	H P 20	63.5
65 per cent grade	H P 21	61.25
50 per cent grade	H P 22	62.25
Size		
150 mm x 150 mm	R C 17	40.25
300 mm x 300 mm	R C 18	67.75
380 mm x 380 mm	R C 19	77.25
Flame retardant treatment		
Impregnation 'P'	R R 26	60.0
Impregnation 'O'	F R 27	76.0
Surface Coating 'A'	C C 29	47.0
Protective Encasement		
Asbestos Insulation board	C C 30	67.5

PART 3 - PROGRAMME FOR RESIDUAL STRENGTH

Tests were performed on three 230 mm x 230 mm specimens of Douglas Fir with Urea glue (FU 23, 24 and 25) to determine the ability of the columns to withstand reloading on cooling to ambient conditions and to gauge the strength at high temperatures.

The results of the tests are given over together with the estimated fire resistance of a Douglas fir column of similar type when supporting 50 per cent design load.

Table 6 - Results of tests for residual strength

Specimen	Test Load	Duration of Heating	Residual strength
FU/23	32.1 tons	45 mins	76.8 tons (after cooling for 48 hours)
FU/24	32.1 tons	45 mins	55.75 tons (at the end of heating)
FU/25	24.0 tons	60 mins	> 24.0 tons (after cooling for 48 hours)
FU	32.1 tons	63.2 mins	Collapse expected (From Table 11)

DISCUSSION OF RESULTS

PART 1. STATISTICAL PROGRAMME FOR PRIMARY FACTORS

Statistical analysis

From the balanced block, the mean fire resistance for all columns was found to be 52.47 minutes and from this the mean fire resistance for each individual species was calculated as shown in Table 7. The apparent variation in fire resistance due to species of timber was significant only at the 80 per cent confidence level, i.e. there is one chance in five that the apparent result is erroneous. The difference between the individual species was investigated and a significant difference at the 90 per cent confidence level was found between the results for Douglas fir and Western red cedar which had the highest and lowest values respectively.

The effect due to each of the species was calculated and Table 7 shows the correction factors as percentage values which should be applied to an observed fire resistance to correct for the effect of species.

Table 7 - Mean fire resistance and correction factors for different species

Species	Mean fire resistance (min)	Correction factor/ per cent
Douglas Fir	56.69	90.17
Redwood	55.25	93.02
Hemlock	53.37	103.18
Cedar	44.57	115.53

/Calculated from logarithmic transformations

The mean fire resistance for different types of glues, together with the correction factors are shown in Table 8.

Table 8 - Mean fire resistance and correction factors for each type of glue

Glue type	Mean fire resistance (min)	Correction factors per cent
Phenolic	57.00	91.58
Resorcinol	52.76	97.68
Urea	52.25	99.74
Casein	47.88	112.07

The overall variation in the fire resistance times due to the effect of glue, when examined statistically, was not found to be significant but a significant difference was shown to exist between results for Phenolic and Casein glues at 90 per cent confidence level.

The influence of the shape of the section is shown in Table 9 together with the correction factors.

Table 9 - Mean fire resistance and correction factors for different shapes

Shape	$b/_d$	Dimensions	Mean fire resistance (min)	Correction factors per cent
α	1.00	230 mm x 230 mm	55.53	92.13
β	1.74	305 mm x 175 mm	53.00	98.56
δ	2.71	380 mm x 140 mm	45.81	119.51

The effect of shape was found to be significant at the 90 per cent confidence level and almost significant at the 95 per cent level. Whilst the difference between shapes α and β was significant only at the 75 per cent level, that between β and δ and α and δ was found to be significant at the 85 and 95 per cent confidence levels respectively.

The specimens were subjected to the tests under three different loading conditions; X - 100 per cent design load, Y - 50 per cent design load and Z - 25 per cent design load. The mean fire resistance for different loads and the appropriate correction factors are given in Table 10.

Table 10 - Mean fire resistance and correction factors for various loads

Load	Mean fire resistance (min)	Correction factors per cent
X - 100 per cent design	36.75	141.58
Y - 50 per cent design	57.04	99.77
Z - 25 per cent design	71.06	70.97

The effect of load was found to be very significant at the 99 per cent confidence level and the investigation of the difference between the test loads showed the following significance levels.

100 per cent Design load: 50 per cent design load - 99 per cent confidence limit
100 per cent design load: 25 per cent design load - 99.9 per cent confidence limit
50 per cent design load: 25 per cent design load - 99 per cent confidence limit

The statistical analysis of the balanced programme indicates that the prediction of fire resistance for columns of different shapes and under different loads can be based on the test data. Its application to predict the effect of species and glue has not the same validity but since a statistically significant difference exists between the highest and the lowest values for these variables, it would be reasonable to estimate the performance with other combinations of these variables. Table 11 shows the estimated fire resistance of all possible combinations of timber species and glues, for the three different shapes and when supporting three levels of loading, derived from the application of the appropriate correction factors to the mean fire resistance time for the sixteen tests. The actual performance of the sixteen specimens is shown in brackets for comparison.

Table 11a - Estimated fire resistances* of columns of Douglas Fir with different glues and shape under various loading conditions

Load	Shape	Glue: Urea	Glue: Casein	Glue: Resorcinol	Glue: Phenolic	Fire resistance min
100 per cent design load	α (b/d = 1)	x				44
100 per cent design load	α (b/d = 1)		x			39
100 per cent design load	α (b/d = 1)			x		45
100 per cent design load	α (b/d = 1)				x	48 (45)
100 per cent design load	β (b/d =1.74)	x				41
100 per cent design load	β (b/d =1.74)		x			37
100 per cent design load	β (b/d =1.74)			x		42
100 per cent design load	β (b/d =1.74)				x	45
100 per cent design load	δ (b/d =2.71)	x				34
100 per cent design load	δ (b/d =2.71)		x			30
100 per cent design load	δ (b/d =2.71)			x		35
100 per cent design load	δ (b/d =2.71)				x	37
50 per cent design load	α	x				63 (54)
50 per cent design load	α		x			56
50 per cent design load	α			x		64
50 per cent design load	α				x	69
50 per cent design load	β	x				59
50 per cent design load	β		x			52 (53)
50 per cent design load	β			x		60
50 per cent design load	β				x	64
50 per cent design load	δ	x				48
50 per cent design load	δ		x			43
50 per cent design load	δ			x		49
50 per cent design load	δ				x	53
25 per cent design load	α	x				89
25 per cent design load	α		x			79
25 per cent design load	α			x		91
25 per cent design load	α				x	97
25 per cent design load	β	x				83
25 per cent design load	β		x			74
25 per cent design load	β			x		85
25 per cent design load	β				x	90
25 per cent design load	δ	x				54
25 per cent design load	δ		x			61
25 per cent design load	δ			x		70 (74)
25 per cent design load	δ				x	74

* Calculated to the nearest minute

Table 11b-Estimated fire resistance of columns of Redwood with different glues and shape under various loading conditions

Load	Shape	Glue				Fire resistance
		Urea	Casein	Resorcinol	Phenolic	min
100 per cent design load	α (b/d = 1)	x				43
			x			38
				x		44 (44)
					x	47
	β (b/d = 1.74)	x				40
			x			36
				x		41
					x	44
	δ (b/d =2.71	x				33
			x			29
				x		34
					x	36
50 per cent design load	α	x				61
			x			54 (54)
				x		62
					x	67
	β	x				57
			x			51
				x		58
					x	62
	δ	x				47 (47)
			x			42
				x		48
					x	51
25 per cent design load	α	x				86
			x			76
				x		88
					x	94
	β	x				81
			x			72
				x		82
					x	87 (75)
	δ	x				66
			x			59
				x		68
					x	72

Table 11c - Estimated fire resistance of columns of Western Hemlock with different glues and shape under various loading conditions

Load	Shape	Glue				Fire resistance
		Urea	Casein	Resorcinol	Phenolic	min
100 per cent design load	α (b/d = 1)	x				39
			x			34
				x		39
					x	42
	β (b/d =1.74)	x				36
			x			37
				x		35
					x	39
	δ (b/d =2.71)	x				30
			x			26 (23)
				x		30
					x	32
50 per cent design load	α	x				55
			x			49
				x		56
					x	60 (68)
	β	x				51
			x			46
				x		53 (49)
					x	56
	δ	x				42
			x			38
				x		43
					x	46
25 per cent design load	α	x				78 (73)
			x			69
				x		79
					x	84
	β	x				72
			x			65
				x		74
					x	79
	δ	x				60
			x			53
				x		61
					x	65

Table 11d - Estimated fire resistance of columns of Western Red Cedar with different glues and shape under various loading conditions

Load	Shape	Glue				Fire resistance
		Urea	Casein	Resorcinol	Phenolic	min
100 per cent design load	(b/d =1)	x				34
			x			31
				x		35
					x	38
	(b/d =1.74)	x				32 (34)
			x			29
				x		33
					x	35
	(b/d =2.71)	x				26
			x			23
				x		27
					x	29
50 per cent design load		x				50
			x			44
				x		51 (43)
					x	53
		x				47
			x			41
				x		47
					x	50
		x				38
			x			33
				x		39
					x	41 (39)
25 per cent design load		x				69
			x			62 (61)
				x		71
					x	75
		x				65
			x			57
				x		66
					x	70
		x				53
			x			47
				x		54
					x	58

Effect of Species

The predicted fire resistances of columns using the four species of timber with Phenolic, Casein and Resorcinol glue are shown in Table 12. The results for the different shapes and with different loads are also expressed as a percentage of that for Douglas Fir. Figure 5 shows the performance of 230 mm x 230 mm columns made with different species of wood and phenolic glue; the graph shows the parallel nature of the curves. From Table 12 the mean species effects were found to be as follows:

Douglas Fir	100
Redwood	97
Hemlock	88
Cedar	78

The best performance was obtained from Douglas fir and the lowest from Western red cedar; there was a difference of 22 per cent between them, Hemlock being in the middle of the range and Redwood only slightly inferior to Douglas fir. Structurally Douglas fir is the strongest timber followed by Hemlock, Redwood and Cedar in that order, the last named is also the lightest timber of the four. The differences in the structural strength are not considered to be responsible for the fire behaviour of the species, as the strength differences are taken into account when computing the design loads. The densities of the four species are as shown below; these may have had some bearing on the performance by influencing the rate of charring which is being examined separately in another paper.

Timber Species	Density (moisture content 15 per cent)	
Douglas Fir	37 lb/ft^3	594 kg/m^3
Redwood	34 lb/ft^3	545 kg/m^3
Hemlock	34 lb/ft^3	545 kg/m^3
Cedar	24 lb/ft^3	384.4 kg/m^3

Table 12 - Effect of species on fire resistance

Species	Type of Glue	Fire resistances* of 230 mm x 230 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent F+	min	per cent F	min	per cent F
Douglas fir	Phenolic	48	100	69	100	97	100
Redwood	Phenolic	47	98	67	97	94	97
Hemlock	Phenolic	42	89	60	88	84	87
Cedar	Phenolic	38	79	53	78	75	78

* Fire resistance times taken to nearest minute

\+ per cent F is fire resistance as percentage of that for Douglas fir specimens.

Species	Type of Glue	Fire resistances of 305 mm x 175 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent F	min	per cent F	min	per cent F
Douglas fir	Casein	37	100	52	100	74	100
Redwood	Casein	36	97	51	98	72	97
Hemlock	Casein	32	87	46	89	65	89
Cedar	Casein	29	78	41	78	57	78

Species	Type of Glue	Fire resistances of 380 mm x 140 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent F	min	per cent F	min	per cent F
Douglas fir	Resorcinol	35	100	49	100	70	100
Redwood	Resorcinol	34	97	48	97	68	97
Hemlock	Resorcinol	30	86	43	87	61	88
Cedar	Resorcinol	27	78	39	78	54	77

Note: per cent F is fire resistance as percentage of that for Douglas fir specimens.

Effect of glue

Following the procedure adopted for determining the effect of species, the results showing the effect of glue are given in Table 13 and some of these are illustrated in Fig.6. Phenolic gave the best results followed by Resorcinol, Urea and Casein in that order. From Table 13 the mean glue effect expressed as a percentage of Phenolic was found to be as follows:-

Phenolic	-	100
Resorcinol	-	94
Urea		92
Casein		82

Of the four glues Casein was of organic origin and appeared to decompose at lower temperatures and was observed to permit some delamination to occur during the tests before the laminates had been completely consumed.

In the design of a laminated member no consideration is given in determining the structural design of a section to the type of glue employed. It would appear from the results of these tests that glue can have some influence on performance in the case of a fire test and whilst it may be possible, without introducing large errors, to group together Phenolic, Resorcinol and Urea glues, use of Casein may result in a significant lowering of fire resistance .

Table 13 - Effect of glue on fire resistance

Type of Glue	Timber species	Fire resistances of 230 mm x 230 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent P	min	per cent P	min	per cent P
Phenolic	Douglas Fir	48	100	69	100	97	100
Resorcinol	Douglas Fir	45	94	64	94	91	94
Urea	Douglas Fir	44	92	63	92	89	92
Casein	Douglas Fir	39	82	56	82	79	82

Type of Glue	Timber species	Fire resistances of 305 mm x 175 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent P	min	per cent P	min	per cent P
Phenolic	Hemlock	39	100	56	100	79	100
Resorcinol	Hemlock	37	94	53	94	74	94
Urea	Hemlock	36	92	51	92	72	92
Casein	Hemlock	32	81	46	82	65	83

Type of glue	Timber species	Fire resistances of 380 mm x 140 mm columns					
		100 per cent load		50 per cent load		25 per cent load	
		min	per cent P	min	per cent P	min	per cent P
Phenolic	Cedar	29	100	41	100	58	100
Resorcinol	Cedar	27	92	39	94	54	94
Urea	Cedar	26	91	38	92	53	90
Casein	Cedar	23	81	33	81	47	82

Note: per cent P means fire resistance as percentage of that for specimens with Phenolic glue.

Effect of shape

The three shapes α (230 mm x 230 mm), β (305 mm x 175 mm) and δ (350 mm x 140 mm)were selected to give approximately the same cross sectional area and to provide identical structural properties so that the same test loads were appropriate irrespective of the shape. One of the dimensions was also controlled by the thickness of the laminates, as it was intended to use the same laminates in all cases.

The effect of the three shapes is shown in Table 14 and in Figure 7. If the performance of the square shape α is taken as 100, there was a reduction of 7 and 13 per cent respectively with shapes β and δ.

During a fire test layers of timber from the outside of the column are progressively consumed resulting in a progressive decrease in the size of the undamaged timber and an increase in the slenderness ratio.

Table 14 - Effect of shape on fire resistance

Shape	Timber	Glue	Fire resistance					
			100 per cent load		50 per cent load		25 per cent load	
			min	per cent α	min	per cent α	min	per cent α
b/d=1.00	Douglas Fir	Phenolic	48	100	69	100	97	100
b/d=1.74	Douglas Fir	Phenolic	45	94	64	94	90	94
b/d=2.71	Douglas Fir	Phenolic	37	77	53	77	74	77
b/d=1.00	Hemlock	Urea	39	100	55	100	78	100
b/d=1.74	Hemlock	Urea	36	93	51	93	72	93
b/d=2.71	Hemlock	Urea	30	77	42	77	60	77
b/d=1.00	Cedar	Casein	31	100	44	100	62	100
b/d=1.74	Cedar	Casein	29	93	41	93	57	93
b/d=2.71	Cedar	Casein	23	77	33	77	47	77

Note: per cent α means fire resistance as percentage of that for b/d = 1

The combined effect of these two factors lowers the 'crippling' or ultimate strength of the element, until it coincides with the test load when collapse takes place.

Another effect that shape may have would be due to the variation in the exposed surface area; the greater the amount of exposed surface, the greater the amount of charring that would take place thereby reducing the section at a quicker rate. The surface areas presented by shapes β and δ were $4\frac{1}{2}$ and 13 per cent respectively greater than that of shape α.

The total mean effect of different shapes was as follows, taking shape α to have a value of 100.

Shape α ; 230 mm x 230 mm ; b/d = 1.00 - 100
Shape β ; 305 mm x 175 mm ; b/d = 1.74 - 93
Shape δ ; 380 mm x 140 mm ; b/d = 2.71 - 77

It is therefore obvious that for a given cross-sectional area, a square section would provide the optimum fire resistance.

Effect of load

The design procedures of the Code of Practice 112 enable section sizes to be determined to support safely a given load and conversely for a given section the maximum permissible safe load can be determined. In practice often the structural elements support loads lower than the maximum permissible and it was therefore considered useful to determine the effect of reduction in the loads on fire resistance. Specimens were tested under three conditions of loading, maximum permissible i.e. 100 per cent design load (X), 50 per cent design load (Y) and 25 per cent design load (Z).

The results showing the effect of load are given in Table 15 and shown in Fig.8. The following mean values of the load effect as a percentage of the 100 per cent design load were obtained.

100 per cent design load (X) - 100
50 per cent design load (Y) - 142
25 per cent design load (Z) - 200

It is obvious from these values that the increase in fire resistance was not directly proportional to the reduction in the load. An examination of the values of the fire resistance increments shows a square law in operation i.e. a reduction in load by a factor of 0.5 gave an increment of $\sqrt{\frac{1}{0.5}} = 1.42$ and similarly a reduction to 0.25 gave an increment of $\sqrt{\frac{1}{0.25}} = 2.0$.

Table 15 - Effect of load on fire resistance

Load per cent design	Timber	Glue	Fire resistance					
			b/d = 1.00		b/d = 1.74		b/d = 2.71	
			min	per cent X	min	per cent X	min	per cent X
100	Douglas Fir	Phenolic	48	100	45	100	37	100
50	Douglas Fir	Phenolic	69	142	64	142	53	142
25	Douglas Fir	Phenolic	97	200	90	200	74	197
100	Hemlock	Urea	39	100	36	100	30	100
50	Hemlock	Urea	55	142	51	142	42	142
25	Hemlock	Urea	78	200	72	199	60	200
100	Cedar	Casein	31	100	29	100	23	100
50	Cedar	Casein	44	142	41	142	33	142
25	Cedar	Casein	62	200	57	199	47	200

Note:- per cent X means fire resistance as percentage of that for 100 per cent load

Estimation of fire resistance

The discussion of the results in the primary part of the programme has illustrated the influence of four factors, viz. timber species, glue, shape and the test load, on the fire resistance of laminated timber columns. The statistical analysis has enabled the relative values of these to be evaluated. These can be utilized in predicting the fire resistance of a given column, within the range of factors explored, provided the performance of a reference specimen is known.

An empirical method, based on the results in the statistical part of the programme, has been evolved which permits the fire resistance to be computed. The empirical values for the four factors are given in Table 16 over.

Table 16 - Empirical values of factors to determine fire resistance of columns.

Factor	Empirical value
<u>'T' Timber Species</u>	
Douglas Fir	2.64
Redwood	2.56
Hemlock	2.33
Cedar	2.06
<u>'G' Glue</u>	
Phenolic	2.64
Resorcinol	2.48
Urea	2.43
Casein	2.17
<u>'S' shape</u>	
b/d = 1.00	2.64
b/d = 1.74	2.46
b/d = 2.71	2.04
<u>'L' Load</u>	
100 per cent design load	2.64
50 per cent design load	3.74
25 per cent design load	5.28

Fire resistance in minutes is determined by choosing the appropriate values for the four factors; T, G, S and L, and multiplying these together. For example, to determine the fire resistance of a Redwood column made with Resorcinol glue, having a b/d ratio of 1.74 and supporting a 50 per cent design load, the values of the four factors are found from Table 16.

$$T = 2.56, \quad G = 2.48, \quad S = 2.46 \text{ and } L = 3.74$$

Multiplying these together gives a fire resistance of 58.7 minutes.

In Fig.9 two curves have been drawn to enable the empirical values for the shape and the load factors, 'S' and 'L' to be interpolated.

It is intended to explore this approach further in a subsequent paper to determine the feasibility of estimating the fire resistance of laminated timber columns outside the range of factors explored and the possibility of applying these principles to solid sections. It may be necessary to obtain data on some of the other species which may be used in the construction of columns and the behaviour of columns of greater slenderness ratio.

PART 2. PROGRAMME FOR ADDITIONAL FACTORS

Effect of quality of timber

Timber is a natural material with inherent variability from one piece of wood to another. To make the optimum use of its structural properties it is necessary to know the influence of various features on its strength and to evaluate these when dealing with a given species. It is the practice in timber engineering to grade timber according to its quality and the Code of Practice specifies a method which takes into account the rate of growth, fissures, slope of grain and the size of knots. The grades used for this purpose are referred to in C.P.112 as 75, 65, 50 and 40 per cent of which the 75 per cent grade represents timber with minimum defects. The permissible stresses for various species are related to the grade and reference is made to the basic stresses for timber without any flaws.

For all the other experiments in this investigation, timber of 75 per cent grade was employed but it was considered desirable to determine the influence which the presence of defects may have on its fire resistance.

Tests were performed on columns of one species only, i.e. Western Hemlock, in four different grades, 90, 75, 65 and 50 per cent, 90 per cent grade representing the basic material with virtually no flaws. The specimens were 230 mm square and were made with phenolic glue. The 75 per cent grade specimen gave a fire resistance of 68.5 min and formed part of the statistically planned experiment in part 1. Its predicted fire resistance from Table 11 is 59 minutes.

The 90, 65 and 50 per cent grade specimens (HP 20, 21 and 22) gave fire resistances of 63, 61 and 62 minutes respectively. These are plotted in Fig.10 together with the estimated performance of the 75 per cent grade specimen. It is obvious from the graph that the grade of the timber had virtually no effect on its fire resistance. The slight differences from the straight line are possibly due to the fact that a given grade of timber includes upto a maximum number, combination and distribution of defects from the next highest grade but not necessarily all the permitted defects.

The quality of timber influences the level of stresses to which it can be subjected and the results of the tests have clearly indicated that for a given type of timber its quality can be ignored as a factor influencing its fire resistance provided the code recommendations for the permissible stresses for different grades are followed.

Effect of size

Three specimens of redwood manufactured with casein glue (RC 17,18 and 19) were used to determine the effect of size of the section on its fire resistance. They were tested under 50 per cent design load and the results are given in Table 17 which also includes the result obtained for the 230 mm square column, RC 10.

Table 17 - Fire resistance of columns of different sizes

Specimen Ref	Specimen size mm	Fire resistance min
RC 17	150 x 150	40.0
RC 10	230 x 230	54.0
RC 18	300 x 300	67.0
RC 19	380 x 380	77.0

The results are plotted in Fig.11 and the curve has been tentatively extended to the origin.

When a column of a given size is exposed to the heating conditions with the gradual decomposition of the outer layers there is consequential increase of stresses on the timber section not damaged by the high temperatures. There is also an associated increase in the slenderness ratio, which for a column of a given length is inversely related to the radius of gyration. The first resistance of a given size of column is therefore due to a combined effect of the decrease in the area of the section and a decrease in the radius of gyration. Examination of the fire resistance obtained with the square section of columns of Redwood show that the fire resistance is directly proportional to $d^{0.7}$ where d is the minimum width of the section. The values of $d^{0.7}$ for the four specimens are plotted in Fig.11 against fire resistance and a straight line relationship is apparent, with the curve passing through the origin. It should be possible to develop similar curves for columns manufactured from other types of wood and glue.

Effect of flame retardant treatments

Three specimen columns of 230 mm square cross-section were used to determine the influence of fire retardant treatments on their performance. Specimen RR 26 (Redwood with resorcinol glue) was impregnated with impregnation treatment 'P' at the rate of 400 kg/m^3 (2.5 lb/ft^3) and Specimen FR 27 (Douglas fir with resorcinol glue) with impregnation treatment 'O' at the rate of 530 kg/m^3 (3.3 lb/ft^3). Specimen CC 29 (Western Red Cedar with casein glue) was given a surface coating of a clear intumescent type paint 'A' in three coats and then overpainted with a chlorinated rubber paint. The specimens were tested under 50 per cent design loads and their performance is given in Table 18 below together with the estimated values of performance for similar columns without treatment.

Table 18 - Fire resistance of certain columns with and without fire retardant treatments

Column Ref.	Treatment	Fire Resistance mins
RR 26	Impregnation 'P'	60
FR 27	Impregnation 'O'	76
CC 29	Surface coating 'A'	47
RR	None	62.5 (From Table 11
FR	None	65 (
CC	None	44 (

The results show that whilst treatments 'P' and 'A' have no marked effect on the performance of the specimens, treatment 'O' showed some improvement; this may possibly have been due to the higher rate of impregnation employed.

Effect of Protective Encasement

Specimen CC 30 (Western Red Cedar with casein glue) was protected by a 13 mm encasement consisting of asbestos insulation board screwed to battens. The 230 mm square specimen when subjected to 50 per cent design load gave a fire resistance of 67.5 minutes, as compared with 44 minutes estimated for a similar column without protection. During the test, the encasement prevented rapid rise in the temperature of the timber surface, which attained a temperature of 500°C after 60 minutes exposure. The depth of charring of timber was found to be 23 mm (0.9 in) at the end of the test.

The protective encasement of 13-mm asbestos insulation board increased the fire resistance of the specimen column by just over 20 minutes and is likely to provide a similar increment in the performance of columns of other types.

PART 3, PROGRAMME FOR RESIDUAL STRENGTH

Specimen FU 23 was exposed to the heating conditions under an axial load of 32.1 tons (50 per cent design load) for 45 minutes; further charring of timber was prevented by quenching. On reloading the specimen after a lapse of 48 hours it supported a load of 76.8 tons before collapse.

Specimen FU 24 was heated under identical conditions and at the end of 45 minutes the load was increased until failure occurred under an axial load of 55.75 tons.

Specimen FU 25 was tested when supporting a load of 24 tons (37.5 per cent design load) for 60 minutes and was able to withstand a re-application of the test load on cooling without difficulty. On the basis of the data given in Table 16 and Figure 9, a column of this type under a load of 24 tons would be expected to survive for 74 minutes.

Results of these tests for residual strength have shown that the compression strength of timber is lowered at high temperature but on cooling it is likely to regain a major part of its original strength. On the basis of tests on specimens FU 23 and 24, the reduction in structural properties after heating may be as much as 27 per cent.

It would seem that when the testing of a timber column is terminated prior to collapse, it will be able to withstand re-application of the test load as required by the Standard on fire tests. It is assumed that no further pyrolysis of timber would take place during the cooling period

CONCLUSIONS

An investigation, detailed both experimentally and analytically, has been carried out on the fire resistance of laminated timber columns and the influence of a number of factors has been investigated. Part of the investigation consisted of a statistically planned experiment which enabled the effects of some of the factors to be determined quantitatively. Many basic data have been obtained, some of which, particularly on charring, will be dealt with in a separate paper.

The following conclusions can be drawn from the results discussed in this paper.

1. Timber species have some influence on the performance of laminated columns; of the four species examined Douglas fir gave the best performance closely followed by Redwood and Hemlock. Western red cedar was found to be over 20 per cent lower in performance than Douglas fir.

2. As in the case of species, one of the glues gave appreciably lower results than the others. Phenolic was found to be the best glue followed by Resorcinol, Urea and Casein in that order. Casein, which is of organic origin, was nearly 20 per cent lower in performance than Phenolic glue.

3. As timber species and glue would always be used together, with the number of variables investigated for each, sixteen combinations would be possible. Of these, the Douglas fir/phenolic combination should give the best performance with Cedar/casein at the other end of the scale nearly 35 per cent lower in performance. Douglas fir and Redwood used with Phenolic, Resorcinal or Urea glue should give results in the top range of the scale with no more than 10 per cent variation in the performance.

4. The shape of the section has a marked effect on performance; for a given area of cross-section, the slender sections are likely to give a lower performance owing to rapid increase in the slenderness ratio as compared with a more square profile. This reduction was found to be as much as 20 per cent when the ratio between the breadth and the depth of the section was increased from 1 to 2.7

5. The fire resistance for a given type and size of column is significantly influenced by the loads it is supporting during the test. In the range of load variation from 25 to 100 per cent of that permissible the fire resistance was halved. For the column sizes investigated, fire resistance and load were found to be related by an inverse square law.

6 For the parameters of size and types of columns investigated it has been found possible to predict fire resistance by using an empirical relationship. Fire resistance in minutes is the product of four factors T x G x S x L where

T is a factor related to species of timber

G is a factor related to type of glue

S is a shape factor

and L is a load factor. The ranges of values of these factors are given in the paper. It is reasonable to assume that a similar type of approach would be possible for other shapes and sizes but some further work may be necessary to establish the appropriate values of the factors.

7. The quality of timber controls the maximum stresses to which a column can be subjected but provided the appropriate stresses as specified in the Code of Practice are employed, the quality appears to have no influence on fire resistance.

8. Larger sections gave an improved performance compared with smaller sections; the main effect of size is on the rate at which the slenderness ratio would increase on gradual decomposition of timber from the exposed surfaces. The fire resistance of square sections was found to be a function of $d^{0.7}$ where d is the width of the side.

9. The residual strength of timber at high temperatures in the uncharred part of the section was found to be less than at ambient temperatures. In the case of Douglas fir this reduction was of the order of 25 per cent. However, on cooling, timber regained a large part of the original strength. It can therefore be safely assumed that if a timber element has withstood exposure to the fire conditions without collapse, it is unlikely to do so on cooling provided charring and decomposition can be terminated at the end of heating.

10. The use of fire retardants consisting of either surface coatings or impregnation treatments is not likely to show a significant improvement. In one case an impregnation treatment showed an improvement but it may have been owing to the rate of application.

11. Encasement with non-combustible insulating materials is one way of improving the performance of a timber column. Use of 13-mm asbestos insulation board resulted in a 20 minute increase in the fire resistance of a specimen by delaying the rate of charring.

The results of this investigation have shown the possibility of computing the performance of timber columns. This work should be continued in the analytical field to devise a mathematical model and to find information on the properties of different sizes and shapes outside the range of the present investigation for a more general application of the data.

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APPENDIX I

CALCULATION OF THE DESIGN LOAD FOR THE SPECIMEN COLUMNS

The calculations were made in accordance with the procedure laid down in the British Standard Code of Practice "The Structural use of Timber"[6].

The maximum design load for a given section is determined by the product of basic dry stress x modification factor K_3 x modification factor K_{19} x cross sectional area.

Basic dry stress (C.P. 112 : 1967, p.24)

Douglas Fir	147.6 kgf/cm^2	(2100 lbf/in^2)
Western Hemlock	126.5 kgf/cm^2	(1800 lbf/in^2)
Redwood	112.5 kgf/cm^2	(1600 lbf/in^2)
Western Red Cedar	91.4 kgf/cm^2	(1300 lbf/in^2)

Modification factor K_3 (C.P. 112 : 1967, p.26)

The grade stress for a single grade laminated member may be taken as the product of the basic stress for the timber and the modification factor K_3 for the appropriate grade of timber and number of laminations as given below in Table 19.

Table 19 - Values of Modification factor K_3

Grade	Percentage Grade	Number of laminations	K_3
LA	90	4 or more	1.00
LB	75	5	0.89
		10	0.91
		15	0.92
		20	0.93
LC	50	10	0.82
		15	0.83

Modification factor K19 (CP 112 : 1967, p.35)

The grade stresses in compression are multiplied by a modification factor, K 19, depending on the slenderness ratio and the condition of loading on the compression member.

The slenderness ratio is determined by the quotient of the effective length and the radius of gyration.

The specimen columns were assumed to be restrained in position and direction at both ends because of the end conditions in the testing apparatus. The exposed height of the specimens between supports was 2.97 m (9 ft 9 in), giving an effective length of 0.7 x 2.97 m = 2.08 m (82 in) (CP.112 : 1967, p 37).

The modification factor K 19 is calculated for columns of various sizes used in the investigation as shown in Table 20 below. (As the Code of Practice deals only in Imperial Units these are shown in the Table).

Table 20 - Calculation of factor K_{19}

Section	Radius of gyration	Slenderness ratio	Factor K_{19}
6 in x 6 in	.289 x 6 in = 1.73 in	82/1.73 = 47.3	0.88
9 in x 9 in	2.60 in	31.5	0.935
12 in x 12 in	3.47 in	23.7	0.95
15 in x 15 in	4.34 in	18.9	0.96
7.7 in x 10.5 in	2.22 in	37.1	0.92
5.85 in x 14.25 in	1.69 in	48.7	0.88

The maximum permissible load for a given section is determined by the product of the

Basic dry stress x factor K_3 x factor K_{19} x cross-sectional area

Design loads calculated on this basis are given in Table 21.

Table 21 - Design loads for column specimens

Timber	per cent	Size of section		Design load	
		mm	in	kg	tons
Douglas Fir	75	230 x 230	(9 x 9)	65.3×10^3	(64.2)
Douglas Fir	75	175 x 305	(6.87 x 12.0)	65.3×10^3	(64.2)
Douglas Fir	75	140 x 380	(5.69 x 15.0)	65.3×10^3	(64.2)
Western Hemlock	90	230 x 230	(9 x 9)	61.4×10^3	(60.5)
Western Hemlock	75	230 x 230	(9 x 9)	56.3×10^3	(55.5)
Western Hemlock	65	230 x 230	(9 x 9)	54.2×10^3	(53.5)
Western Hemlock	50	230 x 230	(9 x 9)	50.8×10^3	(50.0)
Redwood	75	150 x 150	(6 x 6)	20.6×10^3	(20.3)
Redwood	75	230 x 230	(9 x 9)	50.1×10^3	(49.4)
Redwood	75	300 x 300	(12 x 12)	91.4×10^3	(90.0)
Redwood	75	380 x 380	(15 x 15)	64.8×10^3	(143.0)
Western Red Cedar	75	230 x 230	(9 x 9)	40.6×10^3	(40.0)

APPENDIX 2

Model set up:

$$y_{ijkl} = A + W_i + G_j + L_k + S_l + Z_{ijkl} \quad / \; i = 1 - 4 \;\ldots\ldots \; (i)$$
$$j = 1 - 4$$
$$k = 1 - 3$$
$$l = 1 - 3$$

where y_{ijkl} is a function of fire resistance time corresponding to species of wood i, type of glue j, load k and shape of section l.

- A is a constant
- W_i respresents the effect of species i on fire resistance
- G_j represents the effect of glue j on fire resistance
- L_k represents the effect of load k on fire resistance
- S_l represents the effect of shape of section l on fire resistance
- Z_{ijkl} is a random variable.

Assumptions made:

1. $Z_{ijkl} \wedge N \; (0, \sigma)$
2. $\Sigma_i W_i = \Sigma_j G_j = 0$
   $L_1 + 2L_2 + L_3 = 0$
   $S_1 + S_2 + S_3 = 0$
3. Interaction terms do not exist.

Since a time variable is involved in the analysis, a logarithmic transformation of the fire resistance times was made. These are given in Table 4.

Analysis:

Summing equation (i) over i, j, k, l and taking means, subject to the assumptions above, we obtain the equations:

$$\bar{y}_{i\ldots} = A + W_i + \bar{Z}_{i\ldots}$$
$$\bar{y}_{.j..} = A + G_j + \bar{Z}_{.j..}$$
$$\bar{y}_{..k.} = A + L_k + \bar{Z}_{..k.}$$
$$\bar{y}_{\ldots l} = A + S_l + \bar{Z}_{\ldots l}$$
$$\bar{y}_{\ldots\ldots} = A + \bar{Z}_{\ldots\ldots}$$

Subtracting we have

$$\bar{y}_{i\cdots} - \bar{y}_{\cdots\cdot} = W_i + \bar{Z}_{i\cdots} - \bar{Z}_{\cdots\cdot} \quad \ldots\ldots \text{ Effect of species}$$
$$\bar{y}_{\cdot j\cdot\cdot} - \bar{y}_{\cdots\cdot} = G_j + \bar{Z}_{\cdot j\cdot\cdot} - \bar{Z}_{\cdots\cdot} \quad \ldots\ldots \text{ Effect of glue}$$
$$\bar{y}_{\cdot\cdot k\cdot} - \bar{y}_{\cdots\cdot} = L_k + \bar{Z}_{\cdot\cdot k\cdot} - \bar{Z}_{\cdots\cdot} \quad \ldots\ldots \text{ Effect of load}$$
$$\bar{y}_{\cdots l} - \bar{y}_{\cdots\cdot} = S_l + \bar{Z}_{\cdots l} - \bar{Z}_{\cdots\cdot} \quad \ldots\ldots \text{ Effect of section shape}$$

Analysis of Variation

Effect	Sum of squares	Degrees of Freedom	Mean Square	F-ratio	Significance
Species (W)	$4\sum_i(\bar{y}_{i\cdots} - \bar{y}_{\cdots\cdot})^2$ = 0.0284 ...... (a)	3	$\frac{a}{3} = a'$ = 0.0095	a'/v' = $\frac{0.0095}{0.0041}$	2.4 Significant only at 20 per cent level.
Glue (G)	$4\sum_j(\bar{y}_{\cdot j\cdot\cdot} - \bar{y}_{\cdots\cdot})^2$ = 0.0160 ...... (b)	3	$\frac{b}{3} = b'$ = 0.0053	b'/v' = $\frac{0.0053}{0.0041}$	1.3 Not significant at 20 per cent level.
Load (L)	$4 \times (\bar{y}_{\cdot\cdot 1\cdot} - \bar{y}_{\cdots\cdot})^2 +$ $8 \times (\bar{y}_{\cdot\cdot 2\cdot} - \bar{y}_{\cdots\cdot})^2 +$ $4 \times (\bar{y}_{\cdot\cdot 3\cdot} - \bar{y}_{\cdots\cdot})^2$ = 0.1799 ...... (c)	2	$\frac{c}{2} = c'$ = 0.08995	c'/v' = $\frac{0.08995}{0.0041}$	22.8 Significant at 0.1 per cent level.
Shape (S)	$8 \times (\bar{y}_{\cdots 1} - \bar{y}_{\cdots\cdot})^2 +$ $4 \times (\bar{y}_{\cdots 2} - \bar{y}_{\cdots\cdot})^2 +$ $4 \times (\bar{y}_{\cdots 3} - \bar{y}_{\cdots\cdot})^2$ = 0.0343 ...... (d)	2	$\frac{d}{2} = d'$ = 0.0175	d'/v' = $\frac{0.0175}{0.0041}$	4.4 Significant at the 10 per cent level.
Residual	Total - (a + b + c + d) = 0.02045	5	$\frac{\text{Residual S of S}}{5}$ = 0.0041 = v'		
Total	$\sum_i \sum_j \sum_k \sum_l (\bar{y}_{ijkl} - \bar{y}_{\cdots\cdot})^2$ = 0.027905	15			

Estimation of significant effects

Load

Effect of load

	Arithmetic mean of log	Geometric mean min.	Arithmetic mean min.
Mean effect of load $X = \frac{\Sigma X}{4} =$	1.5503	35.5	36.7
" " " " $Y = \frac{\Sigma Y}{8} =$	1.7023	50.4	51.0
" " " " $Z = \frac{\Sigma Z}{4} =$	1.8502	70.8	71.0

Standard error for load factor

$$S.E._X = \sqrt{\frac{v'}{4}} = 0.0321$$

$$S.E._Y = \sqrt{\frac{v'}{8}} = 0.0226$$

$$S.E._Z = \sqrt{\frac{v'}{4}} = 0.0321$$

Standard error of difference Y : X and Y : Z

$$S.E._{Y:X} \text{ and } S.E._{Y:Z} = \sqrt{\frac{v'}{8} + \frac{v'}{4}}$$

$$= 0.0393$$

Significance of difference Y : X and Y : Z

$$\frac{\text{Difference}_{X-Y}}{\text{S.E. difference } X : Y} = \frac{0.1520}{0.0393} = 3.9$$

From error function tables, the difference is almost significant at the 1 per cent level.

$$\frac{\text{Difference}_{Y-Z}}{\text{S.E. difference } Y : Z} = \frac{0.1479}{0.0393} = 3.8$$

Standard error of difference X : Z

$$S.E._{X:Z} = \sqrt{\frac{v'}{4} + \frac{v'}{4}}$$

$$= 0.0453$$

Significance of difference X : Z

$$\frac{\text{Difference}_{X - Z}}{\text{S.E. difference } X : Y} = \frac{0.2999}{0.0453} = 6.6$$

From error function tables, the difference is significant at the 0.1 per cent level.

Shape

Effect of Shape

				Arithmetic mean of logs	Geometric mean min.	Arithmetic mean min.
Mean effect of shape α	=	$\frac{\Sigma\alpha}{8}$	=	1.7369	54.6	55.5
" " " " β	=	$\frac{\Sigma\beta}{4}$	=	1.7076	51.0	53.0
" " " " δ	=	$\frac{\Sigma\delta}{4}$	=	1.6239	42.1	45.8

Standard error for shape factor

$$\text{S.E.}_{\alpha} = \sqrt{\frac{v'}{8}} = 0.0226$$

$$\text{S.E.}_{\beta} = \sqrt{\frac{v'}{4}} = 0.0321$$

$$\text{S.E.}_{\delta} = \sqrt{\frac{v'}{4}} = 0.0321$$

Standard error of difference $\alpha : \beta$ and $\alpha : \delta$

$$\text{S.E.}_{\alpha:\beta} \text{ and } \text{S.E.}_{\alpha:\delta} = \sqrt{\frac{v'}{8} + \frac{v'}{4}}$$

$$= 0.0393$$

Significance of difference $\alpha : \beta$ and $\alpha : \delta$

$$\frac{\text{Difference}_{\alpha - \beta}}{\text{S.E. difference}_{\alpha:\beta}} = \frac{1.7369 - 1.7076}{0.0393} = 0.74$$

From error function tables, the difference is not significant

$$\frac{\text{Diference}_{\alpha - \delta}}{\text{S.E. difference}_{\alpha:\delta}} = \frac{1.7369 - 1.6239}{0.0393} = 2.9$$

A significant difference is shown at the 5 per cent level

Standard error of difference $\beta : \delta$

$$S.E._{\beta:\delta} = \sqrt{\frac{v'}{4} + \frac{v'}{4}}$$

$$= 0.0453$$

Significance of difference $\beta : \delta$

$$\frac{\text{Difference}_{\beta - \delta}}{\text{S.E. difference}_{\beta:\delta}} = \frac{1.7076 - 1.6239}{0.0453} = 1.85$$

From the error function tables, the difference may be just significant at the 15 per cent level.

Species

The difference between the effect due to the use of Douglas Fir and Western Red Cedar may be tested for significance.

Standard error of difference F : C

$$S.E._{F:C} = \sqrt{\frac{v'}{4} + \frac{v'}{4}}$$

$$= 0.0453$$

Significance of difference F : C

$$\frac{\text{Difference}_{F - C}}{\text{S.E. difference } F : C} = \frac{0.1076}{0.0453} = 2.38$$

There is a significant difference at the 10 per cent level

Glue

The difference between the effect due to the use of phenolic and casein glues may be tested for significance.

Standard error of difference P : C

$$S.E._{P:C} = \sqrt{\frac{v'}{4} + \frac{v'}{4}}$$

$$= 0.0453$$

Significance of difference P : C

$$\frac{\text{Difference}_{P - C}}{\text{S.E. difference } P : C} = \frac{0.0877}{0.0453} = 1.94$$

There is a significant difference only at the 15 per cent level.

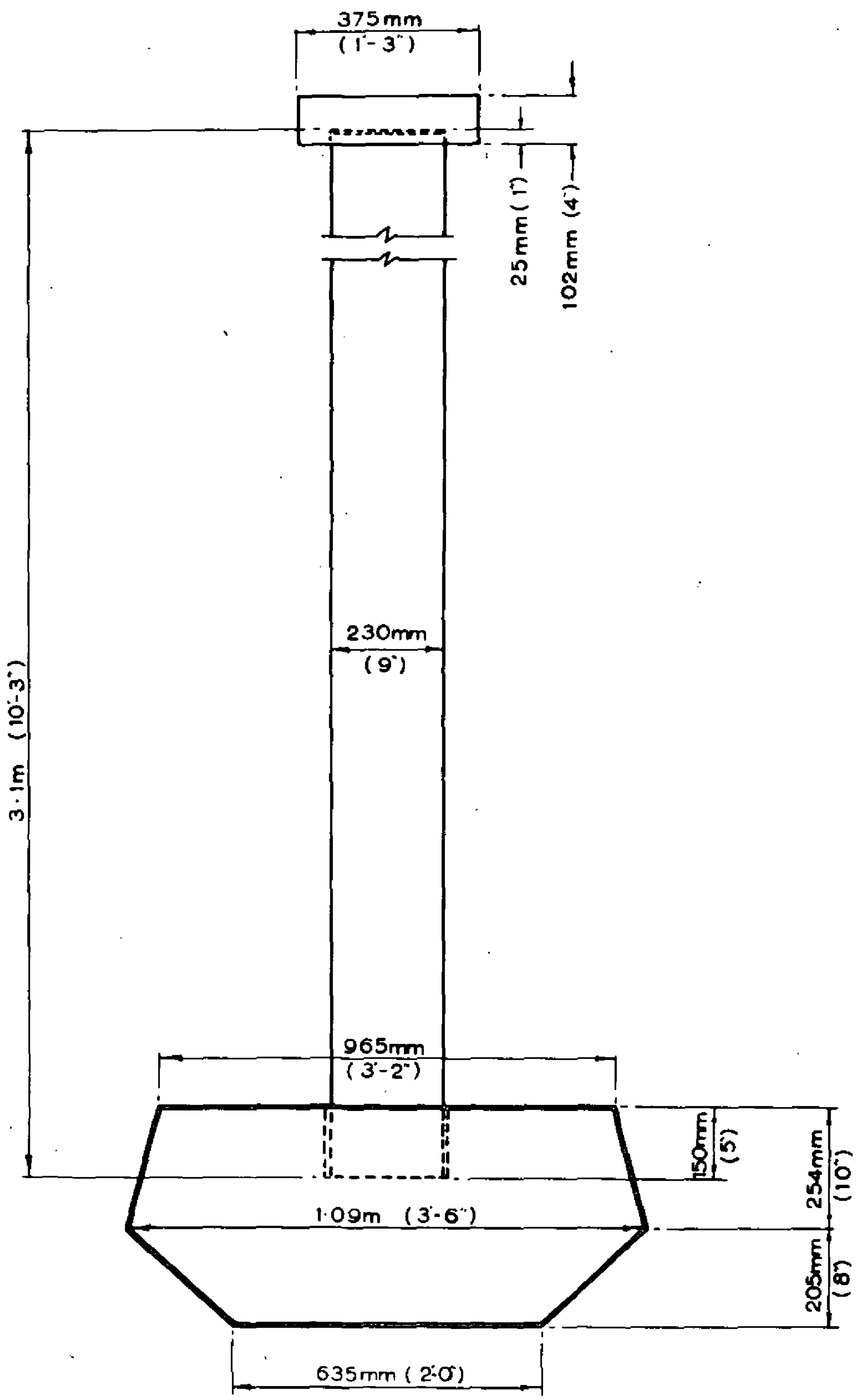
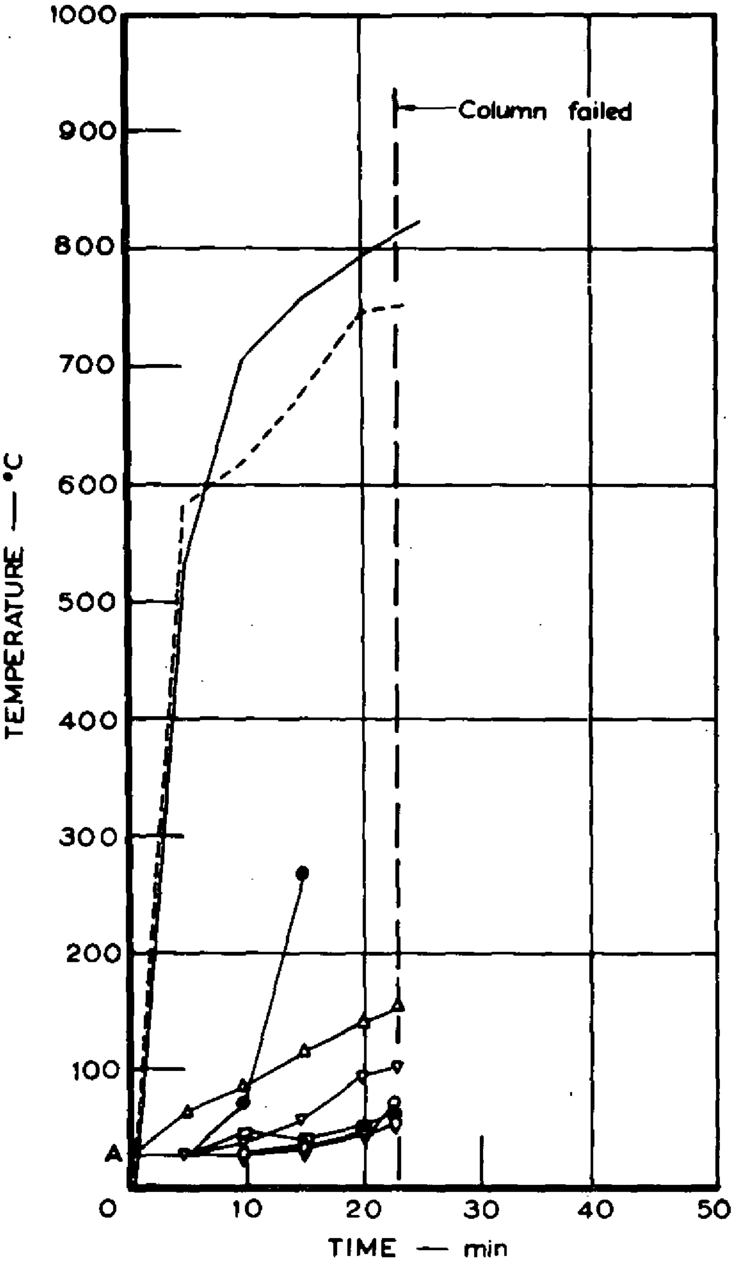


FIG.1. LAMINATED TIMBER COLUMN MOUNTED FOR TEST

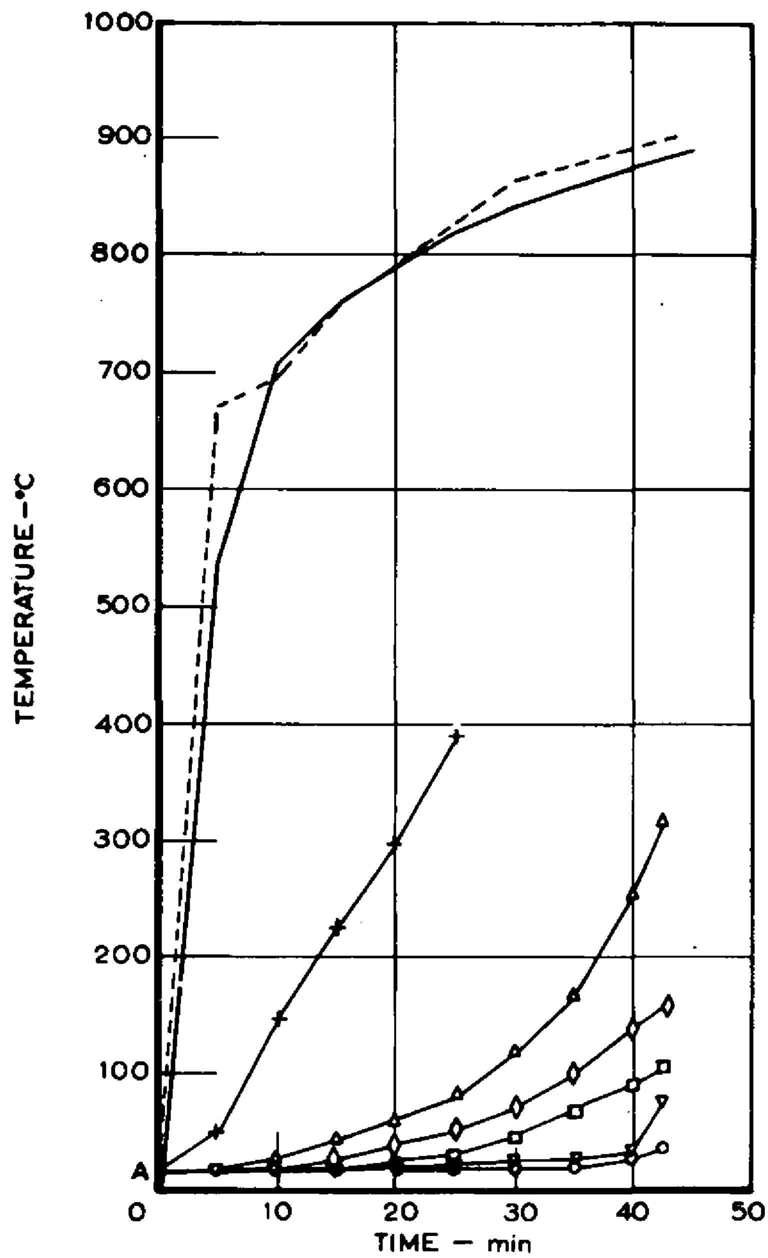


T.C. No.	Symbol	Depth mm	Depth in	
1 and 6	—o—	72	$2\frac{7}{8}$	No. 1 only 51 mm (2 in) from edge
2	—▽—	51	2	
3	—□—	72	$2\frac{7}{8}$	
4	—◇—	72	$2\frac{7}{8}$	
5	—△—	25	1	
7	—●—	72	$2\frac{7}{8}$	25 mm (1 in) from edge

——— B.S. 476 temperature-time curve

- - - - Actual mean furnace temperature

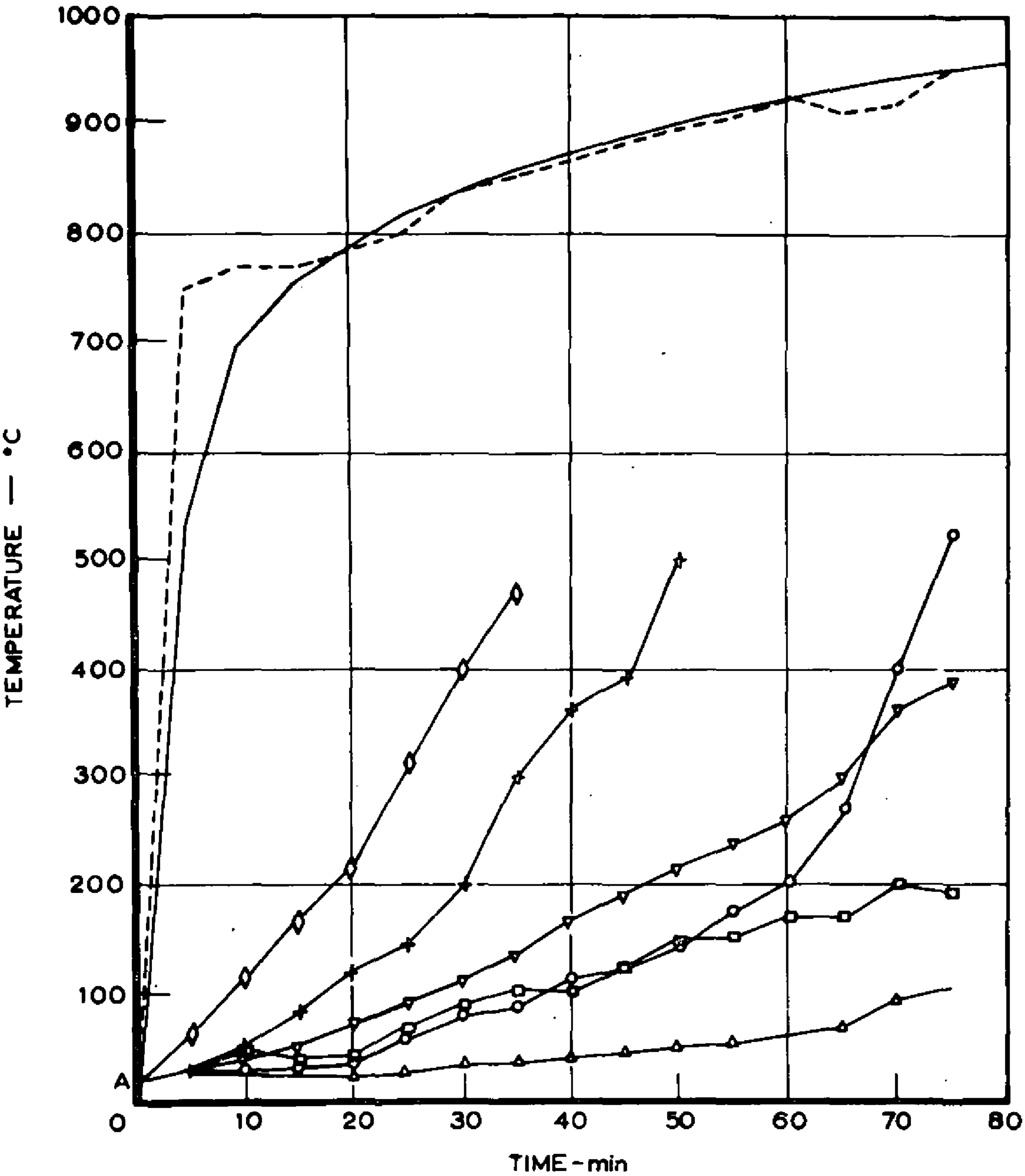
FIG. 2. TEMPERATURE-TIME CURVES FOR COLUMN HG/6



T.C.No.	Symbol	Depth mm	in
1	—o—	114	4½
2	—▽—	72	2⅞
3	—□—	57	2¼
4	—◇—	47	1⅞
5	—△—	38	1½
6	—+—	19	¾

——— B.S. 476 temperature-time curve
- - - - Actual mean furnace temperature

FIG. 3. TEMPERATURE-TIME CURVES FOR COLUMN CR/15

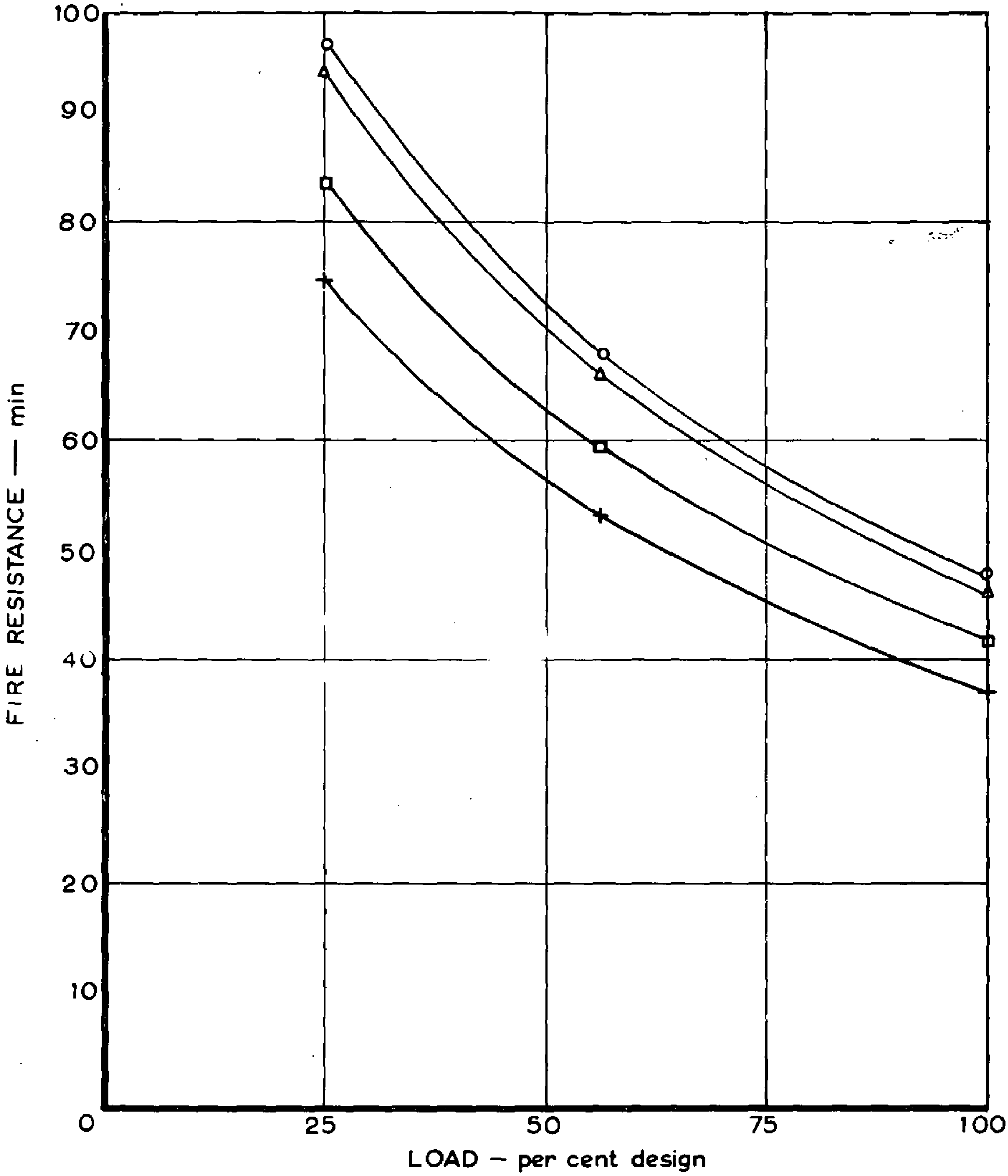


T.C.No.	Symbol	Depth mm	Depth in	
1	—○—	83	3¼	50mm (2in) from edge
2	—▽—	51	2	
3	—□—	63	2½	
4	—◇—	25	1	
5	—△—	83	3¼	
6	—+—	83	3¼	25mm (1in) from edge

——— B.S. 476 temperature-time curve

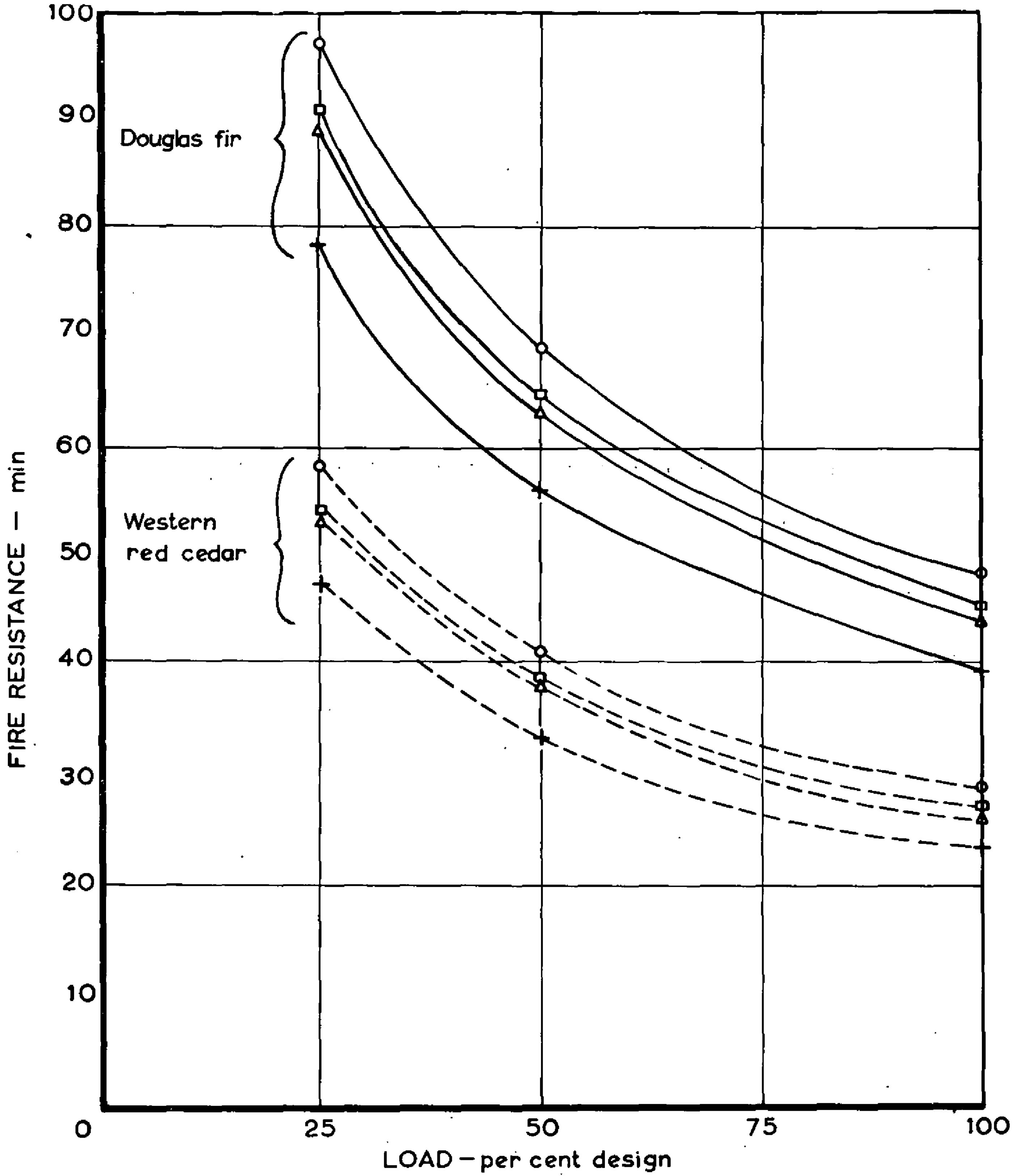
- - - - Actual mean furnace temperature

FIG.4. TEMPERATURE-TIME CURVES FOR COLUMN RP/12



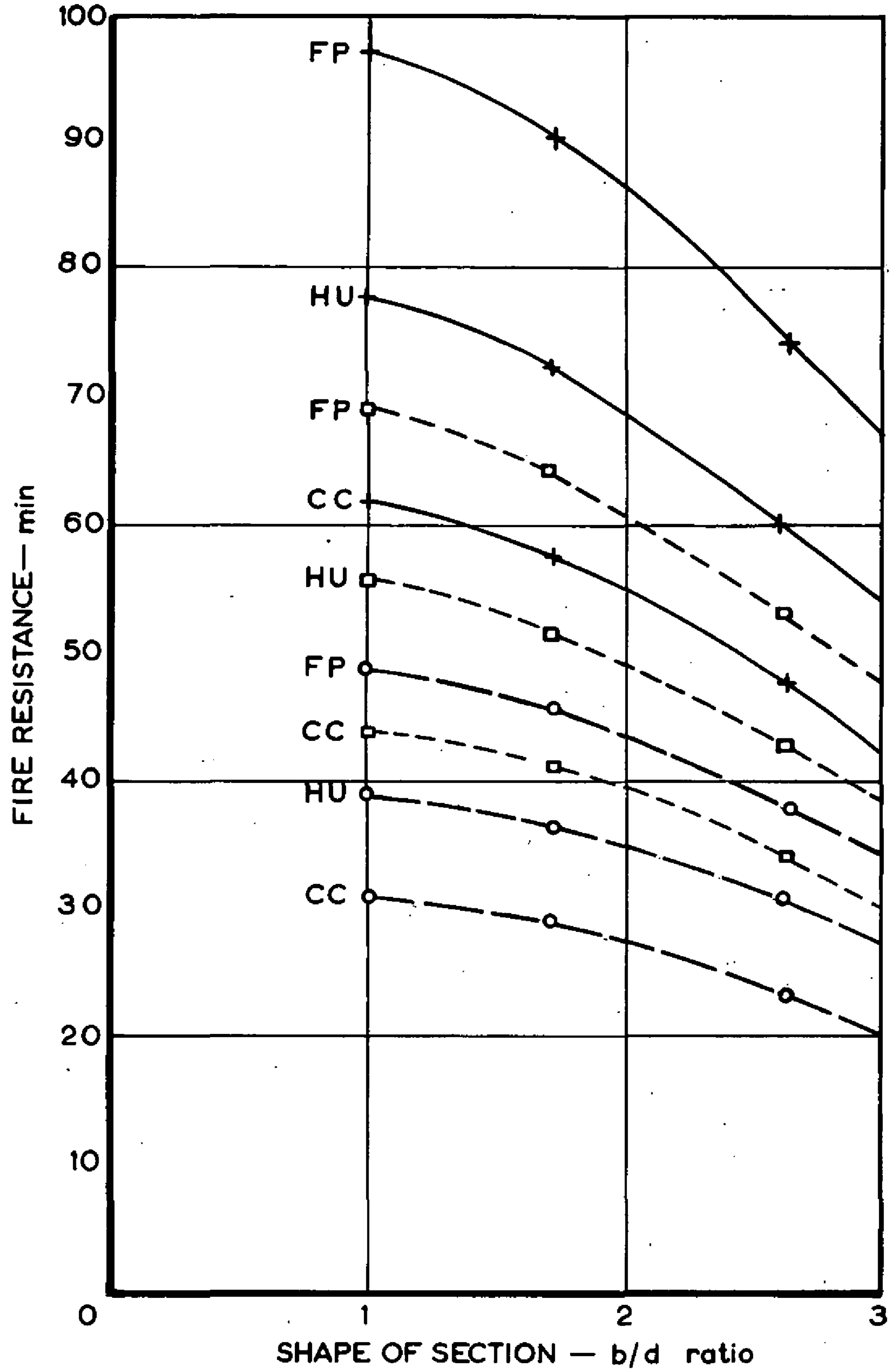
Symbol	Species/glue	
—o—	Douglas fir /	Phenolic
—△—	Redwood /	Phenolic
—□—	Hemlock /	Phenoilc
—+—	Western red cedar /	Phenolic

FIG.5. EFFECT OF SPECIES ON FIRE RESISTANCE OF 230mm (9") x 230mm (9") COLUMNS



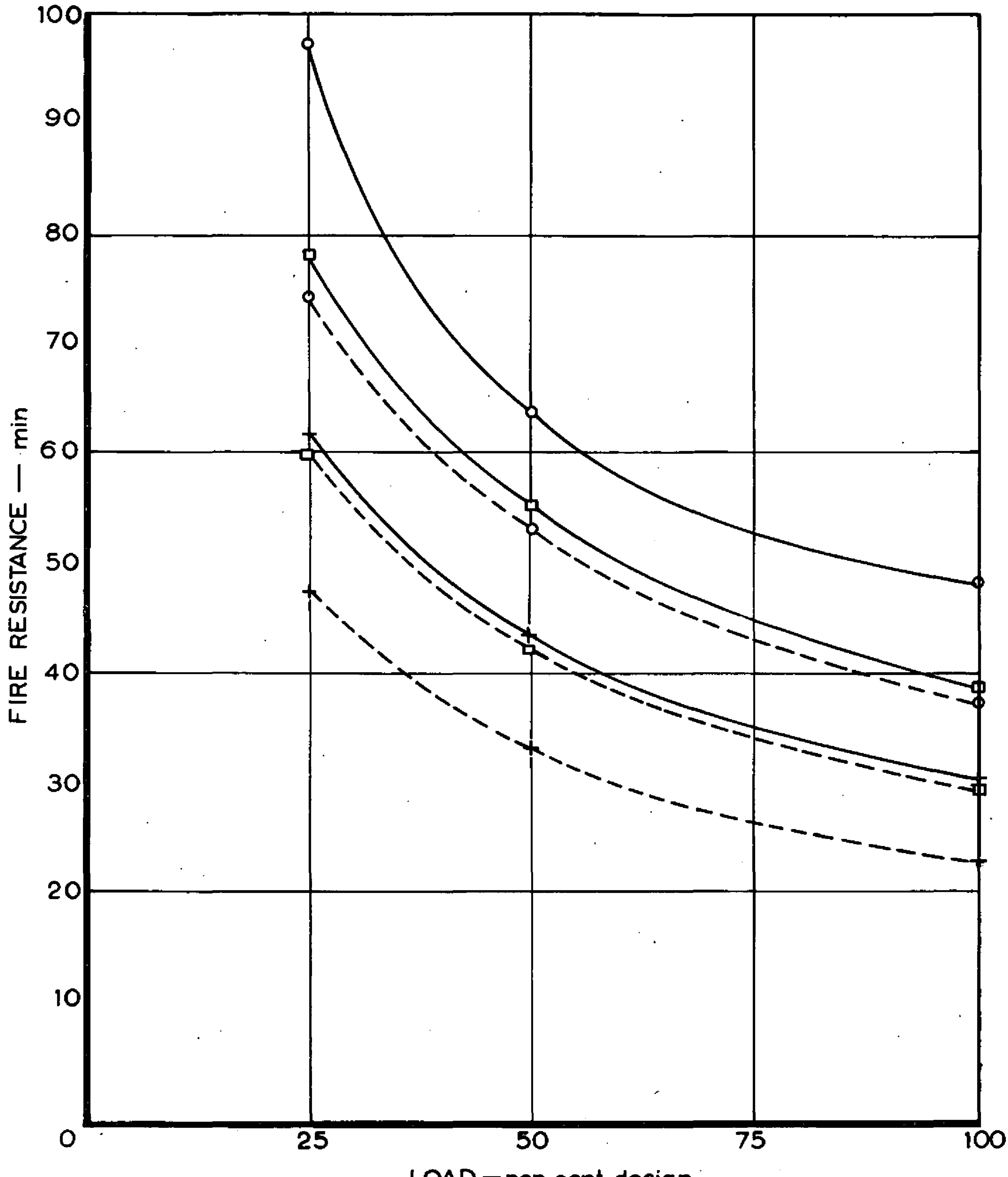
Section 230mm (9")x230mm (9")	Section 140mm (5 11/16")x380mm (15")	Glue
—○—	---○---	Phenolic
—□—	---□---	Resorcinol
—△—	---△---	Urea
--+---	---+---	Casein

FIG.6. EFFECT OF GLUE ON FIRE RESISTANCE



Symbol	Percentage design load	Species/glue
—o—	100	FP Douglas fir / Phenolic
--□--	50	HU Hemlock / Urea
—+—	25	CC Western red cedar / Casein

FIG. 7. EFFECT OF SHAPE ON FIRE RESISTANCE



Section 230mm (9")x230mm(9")	Section 140mm (5 11/16")x380mm (5")	Species / glue
—o—	- - -o- - -	Douglas fir / Phenolic
—□—	- - -□- - -	Hemlock / Urea
—+—	- - -+- - -	Western red cedar / Casein

FIG. 8. EFFECT OF LOAD ON FIRE RESISTANCE

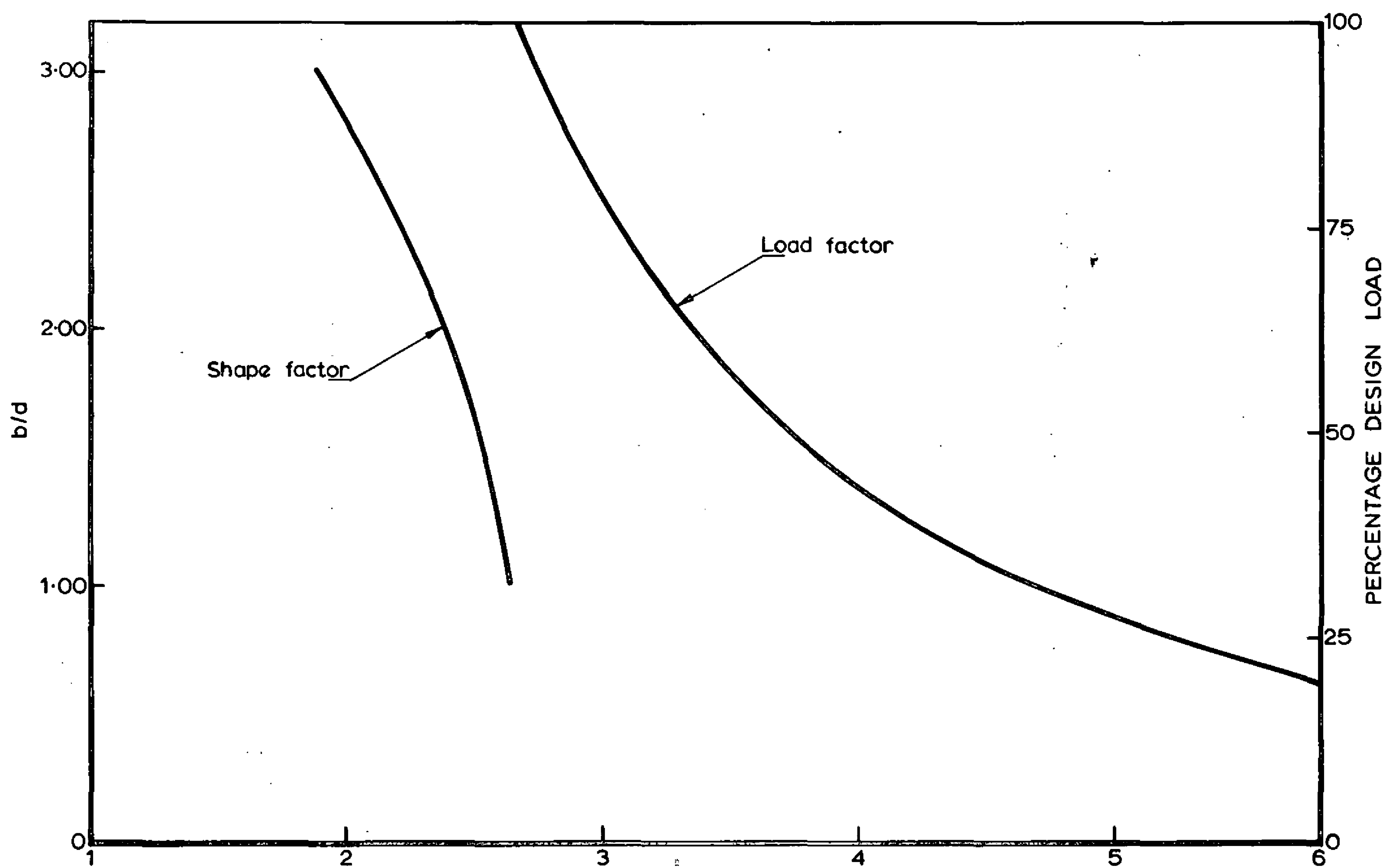


FIG. 9. SHAPE FACTOR AND LOAD FACTOR

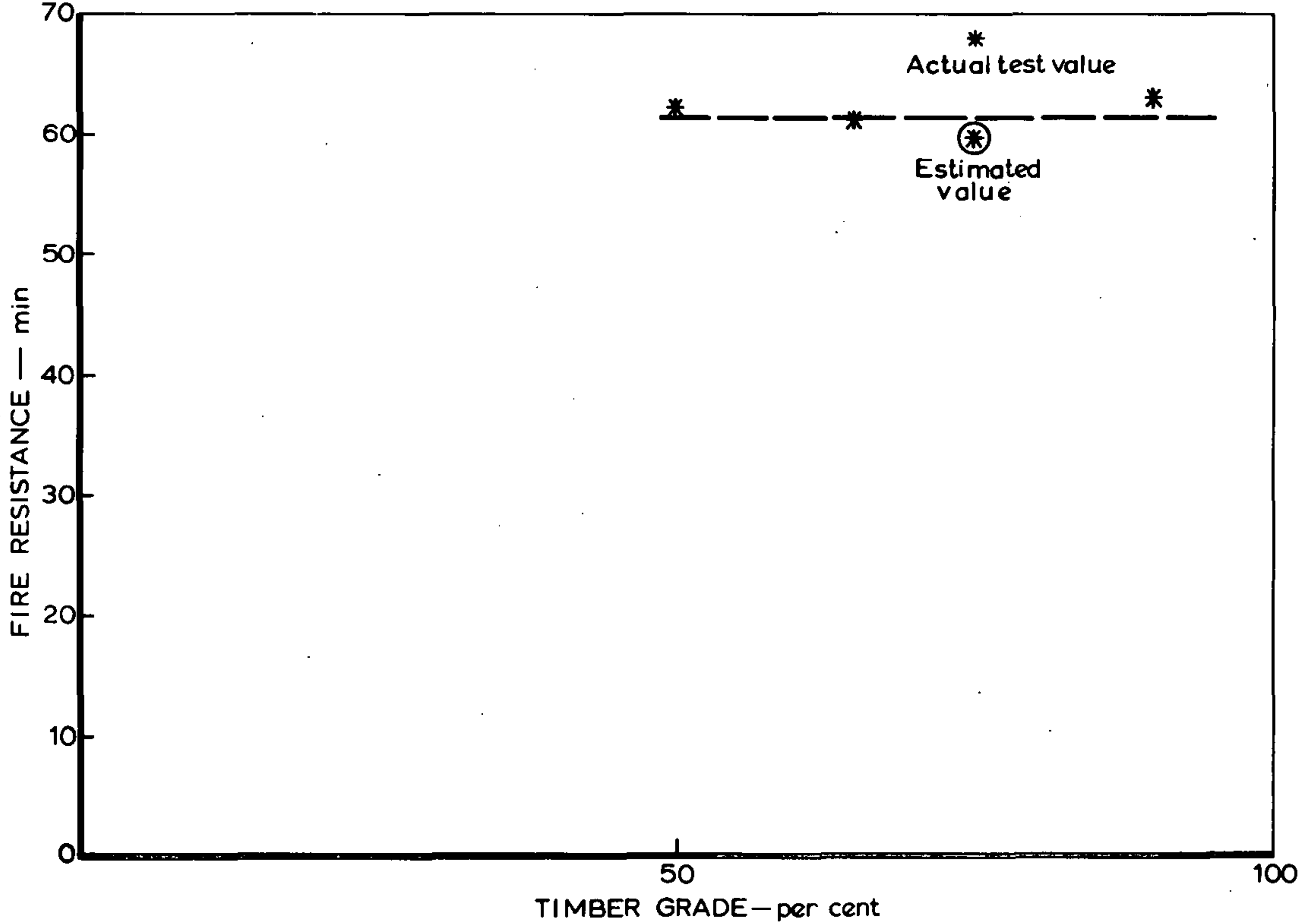


FIG.10. EFFECT OF QUALITY OF TIMBER ON FIRE RESISTANCE

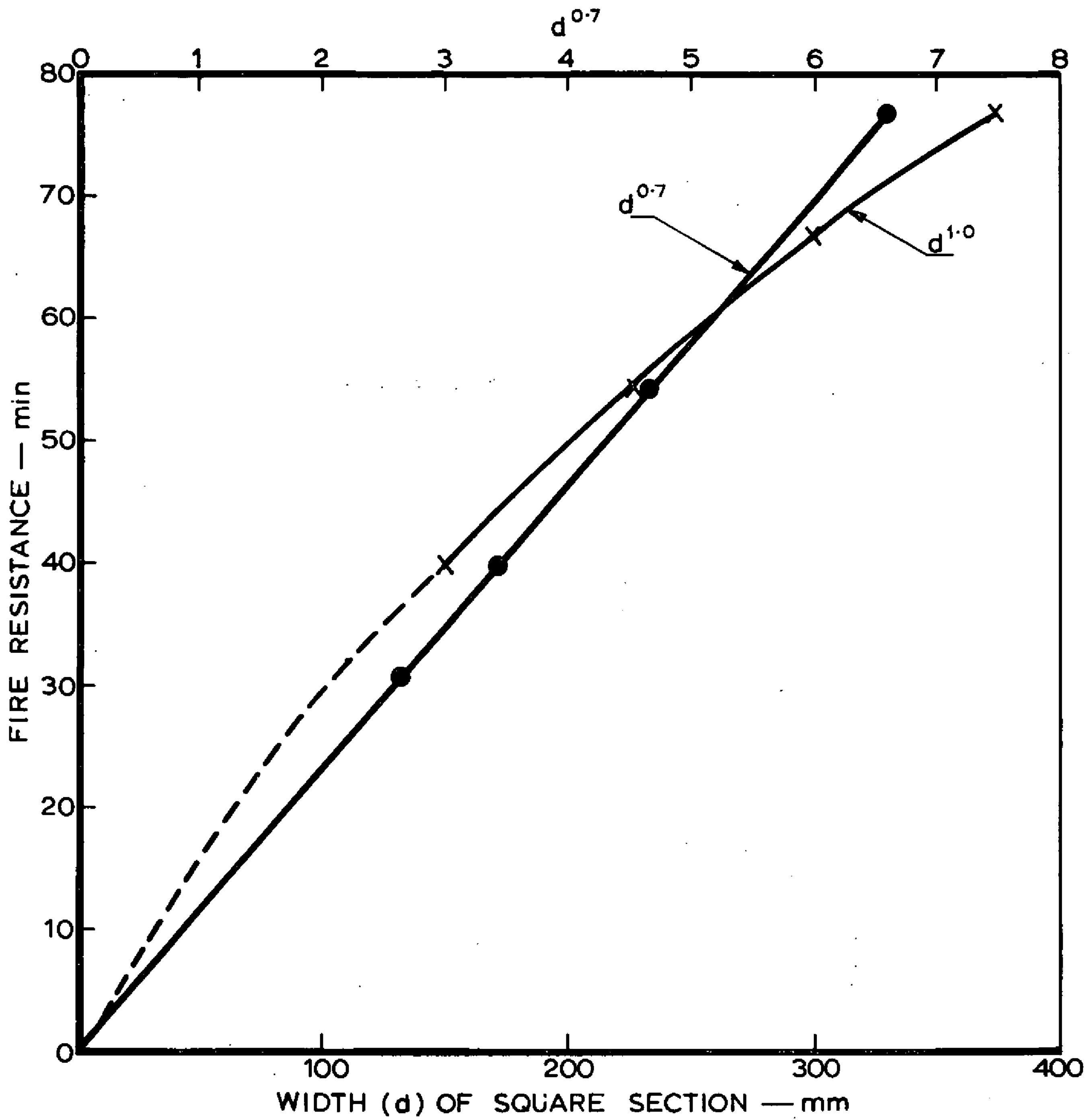
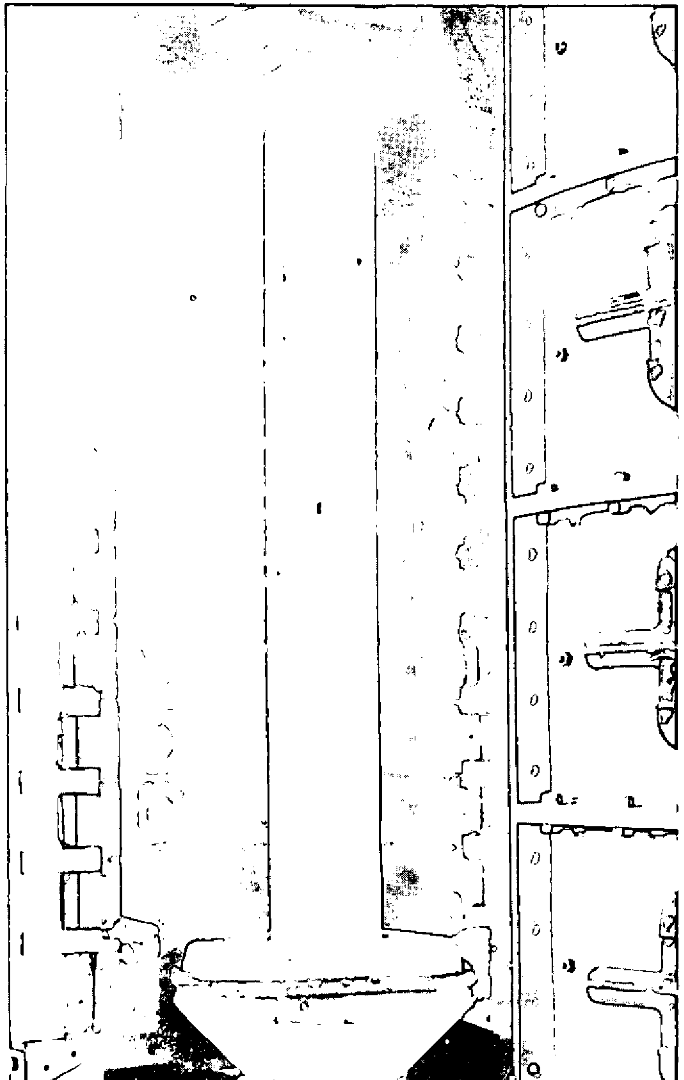
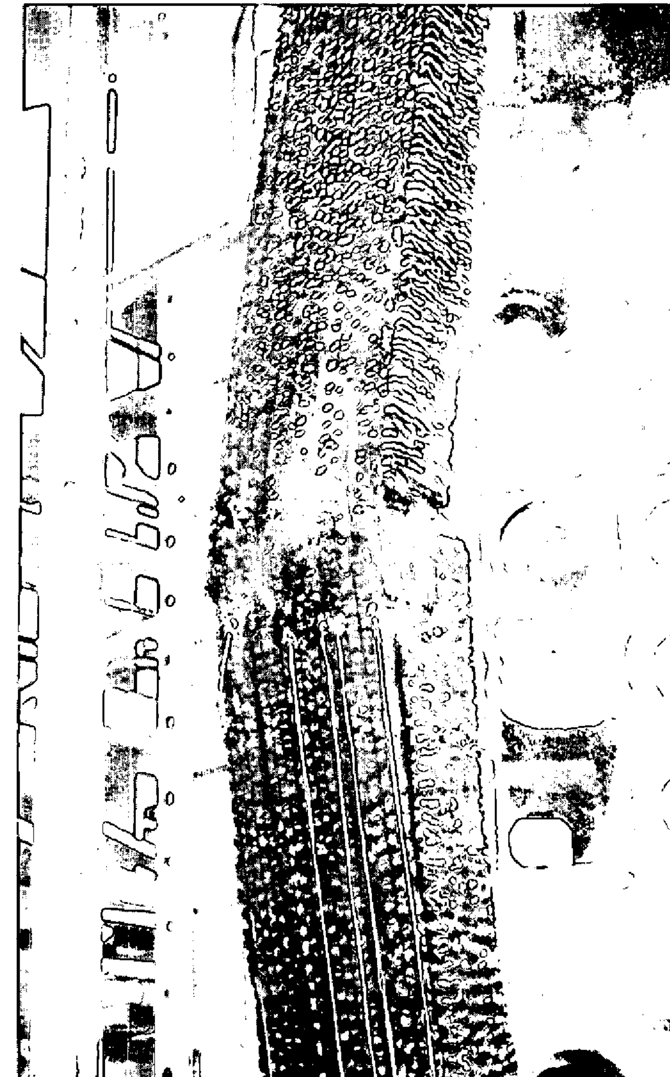


FIG. 11. EFFECT OF SIZE OF SECTION ON FIRE RESISTANCE

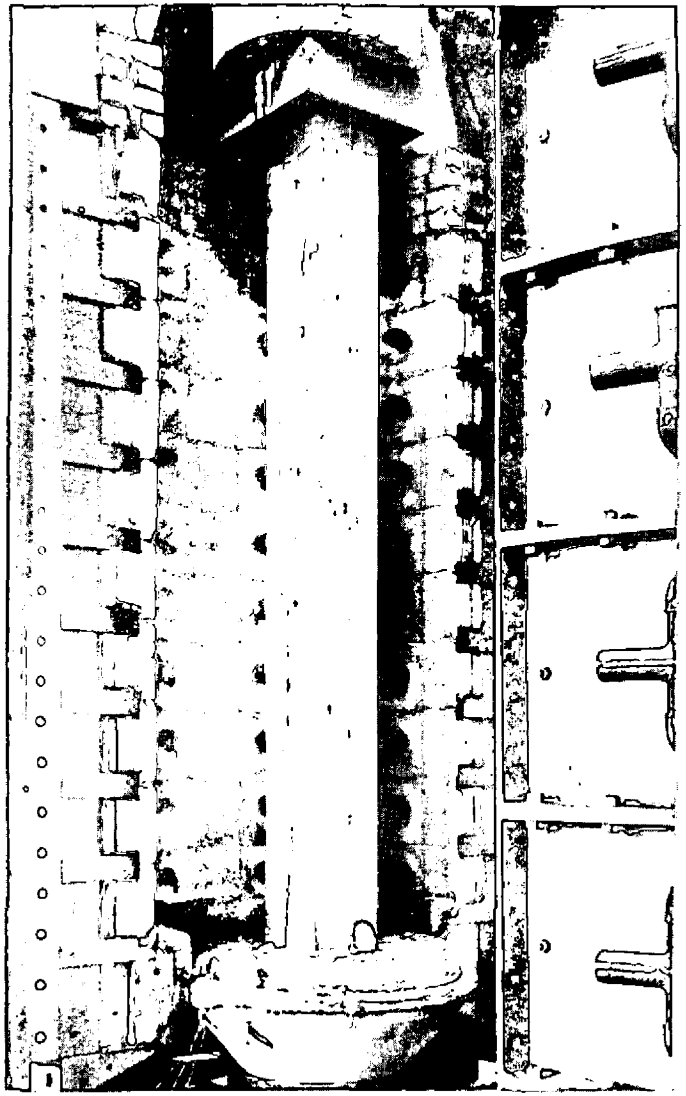


Before test

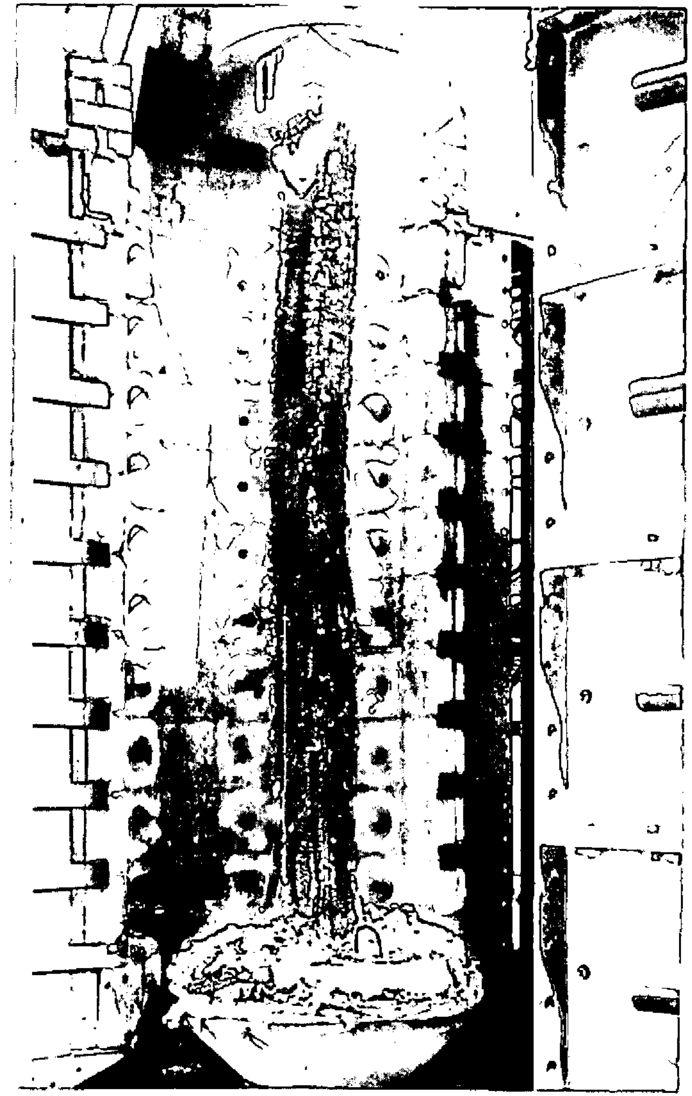


After test

FIRE TEST ON COLUMN HC/6
PLATE 1



Before test



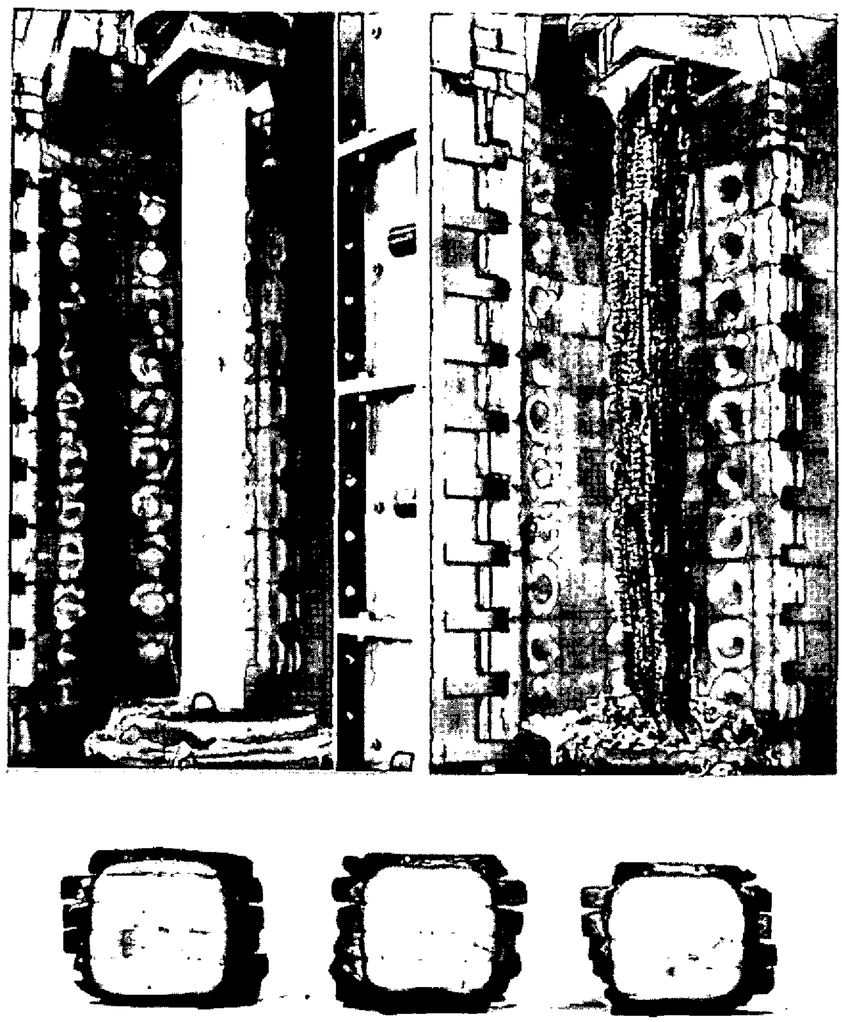
After test

FIRE TEST ON COLUMN RC/19
PLATE 2

During test

After test

FIRE TEST ON COLUMN
PLATE 3



TOP CENTRE BOTTOM

COMPOSITE SHOWING COLUMN FU/ BEFORE AND AFTER
TEST WITH SECTIONS ILLUSTRATING CHARRING
PLATE 4