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The Fire Resistance of Bare Structural Steel Beams

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THE FIRE RESISTANCE OF BARE STRUCTURAL STEEL BEAMS

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SYNOPSIS

Mathematical models are now available for predicting both the temperature rise and increasing deflection of loaded, bare steel beams during BS476:Part 8 fire resistance tests. In view of the imminent adoption of BS5950 as the new Building Code, the models have been used to study the effect of a wide range of loads on the fire resistance time of a selected beam. The results appear to be convincing but they should be supported by a limited test programme. In addition, the models have been used to show that the failure criteria currently used in the BS476:Part 8 test are not sufficiently scientifically based confirming that furnaces having short spans indicate higher fire resistance times. Alternative failure criteria should be sought before the next revision of BS476:Part 8 and ISO834.

KEY WORDS

3. Fire Resistance
4. +BS 476
5. Beams
6. Mathematical Models
7. +BS5950
8. Section Factor
9. Load(Mechanical)
10. Span
11. Lab Reports
12. Sections(Structural)

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CONTENTS

1. INTRODUCTION

Approved document B2/3/4 of the Building Regulations (1985) recommends that the load bearing members in a structure achieve specified levels of fire resistance time as measured in the BS476:Part 8 test. Depending on the size of the building and the fire load inherent in its contents, the specified levels of fire resistance time can (in England and Wales), be 0.5, 1.0, 1.5, 2.0, or 4.0 h. Prior to 1979 virtually nothing was known about the performance of bare steel beams and columns in the BS476:Part 8 test so it was generally assumed that most of the structural steelwork used in buildings would require some form of external fire protection in order to satisfy the Building Regulations.

A recent survey[1] indicated that the provision of fire protection materials for the load bearing members could account for as much as 30% of the total cost of a steel framed structure. It was therefore decided to carry out a programme of research to provide structural engineers and architects with information on the most economic methods by which to satisfy the Building Regulations requirements. The initial part of this project involved the provision of reliable data on the performance of bare steel members in the BS476:Part 8 fire test.

2. THE STANDARD FIRE TEST

In the standard fire test a length of the structural section in question is loaded to the relevant design stress and then heated at a specified rate until its deflection under load reaches a limiting value at which instant the specimen is deemed to have 'failed'. The time to the instant of 'failure' is the measured fire resistance of the structural element under test. For example, it is normal to test a beam in the simply supported condition with a gauge length of 4.5 m. The beam is capped by slabs of structural quality concrete designed to simulate the floor of the building and it is loaded to the specified design stress by means of hydraulic jacks acting through the concrete, as shown in Fig. 1. This structural sub-assembly is incorporated into the roof of a gas fired test furnace so that at least a 4.0 m length of the beam is subjected to the flames. The air in the furnace is heated so that its temperature follows the ISO temperature-time curve and 'failure' is deemed to have occurred when the vertical deflection at the centre of the beam exceeds a value of 1/30 (span). Thus, when the span is 4500 mm the limiting deflection is 150 mm.

When such a test is carried out on a 254 x 146 mm x 43 kg/m bare steel beam loaded to a design stress of 165 N/mm², which is the maximum value allowed for mild steel (BS4360:Grade 43A) in BS449 (the Design Code), then the limiting deflection is reached after 22 min at which time the temperature of the lower flange is 630-670°C. If the design stress is reduced to 83 N/mm² then the fire resistance time is increased to 27 min by which time the temperature of the lower flange is 730-770°C.

In principle it is possible to carry out such standard fire tests on each size of structural steel section, under various design stresses, and hence build up a matrix of data for structural engineers. However, in practice this is not possible because of the loading limitation of the UK testing facilities. At present it is not possible to fully load a beam if its elastic section modulus is in excess of 1100 cm³ and although slightly larger test furnaces are available abroad the cost of performing BS476:Part 8 fire tests in them is very high. It was, therefore, decided to carry out a number of standard fire tests within the limitations of the UK facilities and to use the data obtained to develop and calibrate a mathematical model for the prediction of the fire resistance times of a much wider range of steel section sizes.

3. THE SECTION FACTOR

The heating rate of a steel section in a fire will be some function of the length of its perimeter, Hp, exposed to the flames and its cross sectional area, A, which is a measure of its heat capacity. The ratio Hp/A is known as the section factor and Fig. 2 plots the time required for the lower flange of a bare steel beam to reach a temperature of 650°C in a standard fire test (BS476:Part 8) as a function of the Hp/A value of the beam. The observed scatter among the results is largely due to the fact that the gas temperature in the test furnace rarely follows the ISO temperature-time curve exactly.

4. MATHEMATICAL MODELLING (THERMAL)

In the thermal model[2] the physical laws governing conduction, radiation and convection are used to predict the changing temperature distribution in the steel beam from an assumed knowledge of the temperature/time characteristic of the atmosphere in the test furnace and the thermal properties of the steel. As none of the fire tests being modelled exceed one hour in duration, a simplifying assumption is made that the temperature of the concrete capping slab does not rise significantly during the experiment. Clearly this would not be true for tests of longer duration and a more comprehensive model is currently under development in which changes in the concrete temperature can be accommodated.

The simple model has been used to predict the times for the lower flange of a wide range of bare steel beams to be heated to 650°C in the standard fire resistance test. Inspection of Fig. 3 shows that the section factor is a useful variable against which to plot the heating time and that, as expected, beams with higher values of Hp/A heat to 650°C much faster than deeper or heavier steel sections. The prediction curve, shown in Fig. 3, can be compared with data obtained from BS476:Part 8 fire tests over a period of seven years as illustrated in Fig. 4. Inspection of this figure indicates that the mathematical model predicts heating times which are marginally longer than the mean values of the experimental data. However the significant scatter inherent in the latter makes it rather meaningless to attempt a further refinement of the model as the adjustment involved would be clearly much smaller than the limits of reproducibility of the BS476:Part 8 test.

BS5950 is the new Code of Practice for the design of steel framed buildings and Part 8 of that code will deal with the specific problem of designing to resist collapse in a fire. In Part 8 limiting temperatures, dependent on load, will be assigned to each structural steel member and the design engineer will be required to ensure that the temperature of the member does not exceed its assigned limiting value in the event of a fire. All fires can be related to the BS476 standard fire by means of the Time Equivalent[3] concept and it is therefore appropriate to use the mathematical model to generate data on the heating rates of the entire range of BS4 beams in the standard fire resistance test. Such a matrix of time to various limiting temperatures as a function of section factor Hp/A is given in Table 1.

5. MATHEMATICAL MODELLING (MECHANICAL)

In stage two of the model the temperature profiles mentioned above are used as input data for a second finite element programme which calculates the changes in stress and deflection of the beam as the theoretical fire test proceeds. This programme is based on FASBUS II which was developed in the USA[4] to study the behaviour of floor systems during fires. Analysis of the deflection/time characteristics of a single floor beam is therefore a special, but relatively simple, case for this computer package.

It was essential that the deflection/time data predicted by the mathematical model should compare favourably with the results of standard fire tests. Three such tests have been carried out by BSC staff at the Warrington Research Centre on 254 x 146 mm x 43 kg/m bare steel beams in the simply supported condition, and so the initial modelling was based on this particular section size. The deflection/time data for the three fire tests are plotted in Fig. 5 along with the predictions of the mathematical model. Inspection of this figure shows that during the intermediate stages of each test the model tends to predict deflections which are marginally low. However as the deflections reach their limiting value of L/30 then the model gives an accurate prediction which, in turn, leads to an accurate assessment of fire resistance time. The data described above assumed a maximum stress, in the flange of each beam, of 165 N/mm^2 which was the maximum design stress used for mild steel (BS4360:Grade 43A) when working to BS449. However, BS5950, the new Building Code, allows the use of a wider range of design stresses and so the mathematical model was subsequently used to study the effect of stress on the behaviour of a simply supported 254 x 146 mm x 43 kg/m bare steel beam in the standard fire test. The predictions are shown in Fig. 6 along with data from relevant fire resistance tests. This figure covers stresses from 292 N/mm^2 (the assumed yield stress of the steel) down to 83 N/mm^2. As expected, with lower stresses the beam resists deformation for longer periods of time and therefore attains a higher limiting temperature. It is difficult, with the small amount of experimental data available, to comment on the accuracy of the model predictions and further fire resistance tests at different loads are required to validate the calculations. As stated above, this is particularly important with the introduction of the new Building Code, BS5950.

BS476:Part 8 states that, whenever possible, fire resistance tests should be carried out on beams using spans equal to those planned in service. In practice, the spans used in the standard fire test are determined by the size of the available testing furnace and, in the UK, this usually limits the span to 4.5 m although, in principle, a test span of 7.0 m is available in the facility at Borehamwood. However, elsewhere in the world furnaces with test spans up to 9.0 m are available. It was therefore pertinent to use the mathematical model to study the span dependence of the fire resistance time to see if any commercial advantage is gained by the use of a particular testing facility. Figure 7 shows a plot of predicted fire resistance (i.e. time to span/30) as a function of the section factor, Hp/A, for bare steel beams tested according to BS476:Part 8 over a span of 4.5 m. Actual test data, obtained at the Warrington Research Centre facility, have also been included. It is clear from Fig. 7 that Hp/A is not a perfect variable with which to describe resistance to deflection but nevertheless the plot indicates that, when tested over a 4.5 m span, bare beams with Hp/A values of less than about 116 m^{-1} should exhibit fire resistance times in excess of 30 min and therefore be suitable for use in 'half hour' buildings. Figure 8 compares the prediction curves for beams tested over 4.5 m and 9.0 m spans and it is clear that lower fire resistance times are predicted for long span tests. In the case of a beam tested over a 9.0 m span the Hp/A value would need to be below 102 m^{-1} to satisfy a 'half hour' requirement.

No test data are available for bare steel beams tested over a 9.0 m span but two fully instrumented tests have been carried out[4] at Metz on fire protected beams. The known thermal data from these tests was used, as input, to check the efficiency of the FASBUS II model in predicting the time to a deflection of L/30 for the two beams in question. Table 2 shows a comparison between the calculated and observed results. The model is evidently suitable for the accurate prediction of deflection when the thermal history and loading conditions of the beam are known.

6. RATE OF DEFLECTION

In view of the fact that 'failure' criteria based on the beam attaining a central deflection which is some fraction of the span lead to fire resistant times which are span dependent, there is some incentive to seek alternative criteria which may be less sensitive to the dimensions of the test piece. In the draft BS476:Part 20 it is stated that: 'The test specimen shall be deemed to have failed if it is no longer able to support the test load. For the purposes of this standard, this shall be taken as either of the following, whichever is exceeded first:

(a) a deflection of L/20; or

(b) where the rate of deflection, calculated over 1 min intervals, on each minute from the commencement of the heating period, exceeds the limit set by the following expression:

$$\text{rate of deflection} = \frac{L^2}{9000d} \text{ mm/min}$$

except that this rate of deflection limit shall not apply before a deflection of L/30 is exceeded

where

L is the clear span of specimen (mm);

d is the distance from the top of the structural section to the bottom of the design tension zone (mm)'

Deflection/time curves have been calculated for two, loaded, bare steel beams and these are shown, in Fig. 9, to have reached deflections of L/30 after 21.4 and 32.1 min respectively. The points at which the rates of deflection exceeded $L^2/9000d$ are arrowed in Fig. 9 and are at 17 and 23 minutes respectively. Thus, in the case of loaded bare steel beams, the critical rate of deflection is already exceeded before the criterion of L/30 is reached. Adoption of a rate of deflection criterion in place of span/30 would therefore reduce the fire resistance time of bare steel beams and in the case of the 610 x 305 mm x 149 kg/m section it would cease to have a half-hour rating.

The rate of deflection criterion is obviously based on an estimation of the point at which the beam begins to experience rapid bending in the fire resistance test and while it gives an unfavourable rating to bare steel beams there may well be examples of composite construction where it could be used to advantage. However there is clearly a need to critically review the technical justification for currently used failure criteria and seek some more scientifically based method, perhaps based on moment resistance at temperature, before the next revision of BS476 and ISO834 take place.

7. CONCLUSIONS

1. A mathematical model has been developed which can accurately predict the heating rates of bare steel beams in the BS476:Part 8 fire resistance test.

2. Data provided by the above model can be used as input to FASBUS II to determine the deflection of a loaded steel beam during the standard fire resistance test.

3. The two programmes have been used to study the effect of load on the limiting temperature and fire resistance times of bare steel beams. Additional test data is needed to confirm the validity of the predictions.

4. The programmes have also been used to study the effect of span on the fire resistance time and it has been shown that test furnaces using shorter spans, indicate higher fire resistance times. This is because the currently used failure criteria are span dependent and more work is necessary to develop a scientifically based failure criterion for the BS476:Part 8 and ISO834 fire resistance tests.

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TABLE 1 HEATING RATES OF BARE STEEL BEAMS IN THE BS476:Part 8 FIRE TEST

Limiting Temperature, °C \ Hp/A, m^{-1}	Time to Reach Limiting Temperature, min											
	60	80	100	120	140	160	180	200	220	240	260	280
500	27.67	23.71	20.61	18.25	16.41	15.01	13.93	13.08	12.38	11.78	11.25	10.77
550	30.74	26.39	22.99	20.38	18.37	16.84	15.65	14.71	13.93	13.28	12.70	12.19
600	34.11	29.36	25.65	22.80	20.61	18.94	17.64	16.61	15.76	15.04	14.42	13.87
650	37.98	32.78	28.75	25.56	23.30	21.49	20.09	18.98	18.06	17.28	16.60	16.02
700	42.77	37.03	32.65	29.40	26.85	24.96	23.50	22.33	21.36	20.52	19.80	19.22
750	50.28	43.87	39.25	35.85	33.16	31.10	29.47	28.19	27.18	26.40	25.81	25.39

Note: The data in the table is applicable to universal beam sections, universal column sections supporting a dense concrete floor.

TABLE 2

Beam Size	Time to a Deflection of L/30	
	Observed	Predicted
838 x 292 mm x 194 kg/m	129 min	134 min
686 x 254 mm x 125 kg/m	134 min	134 min

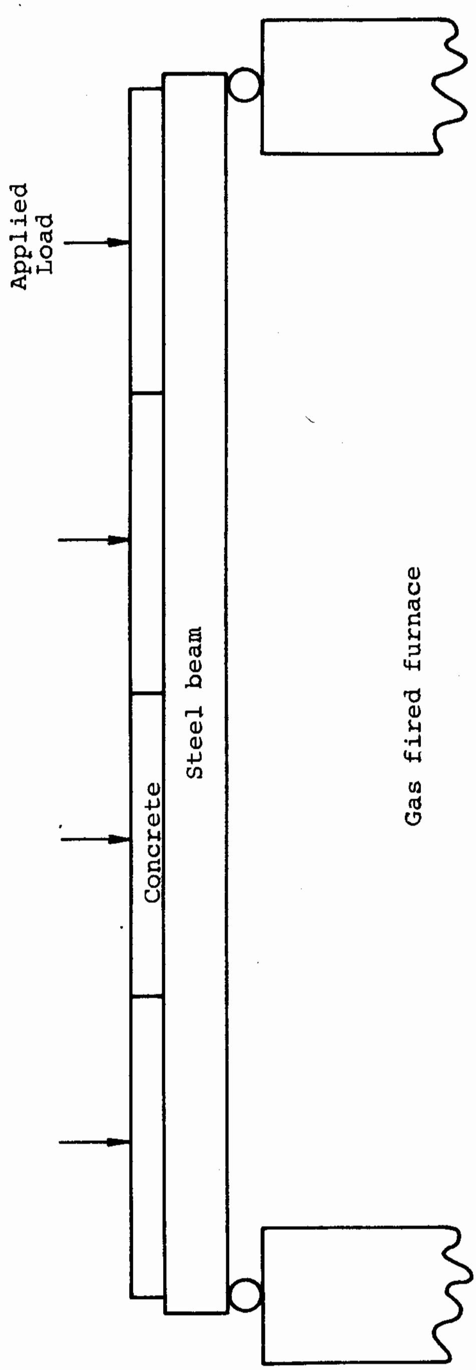
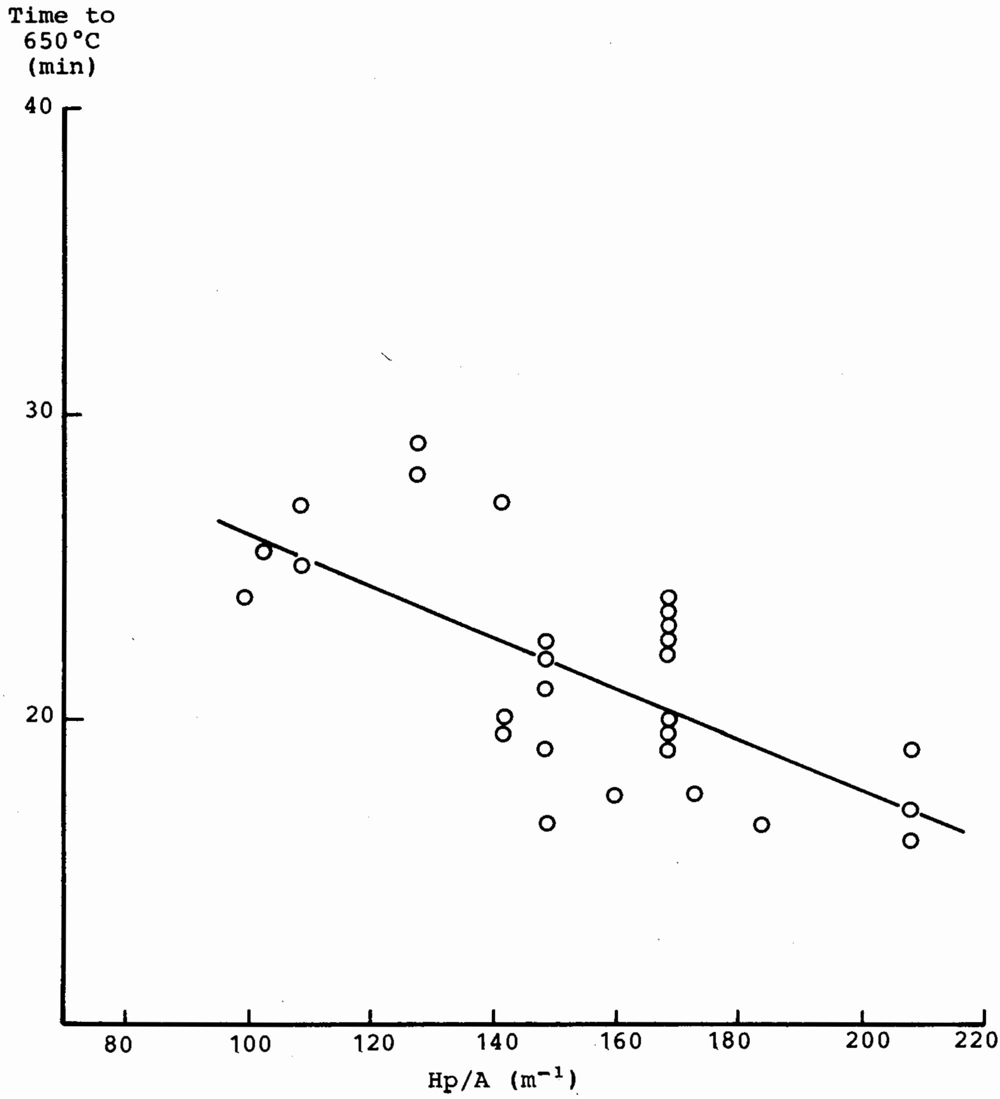


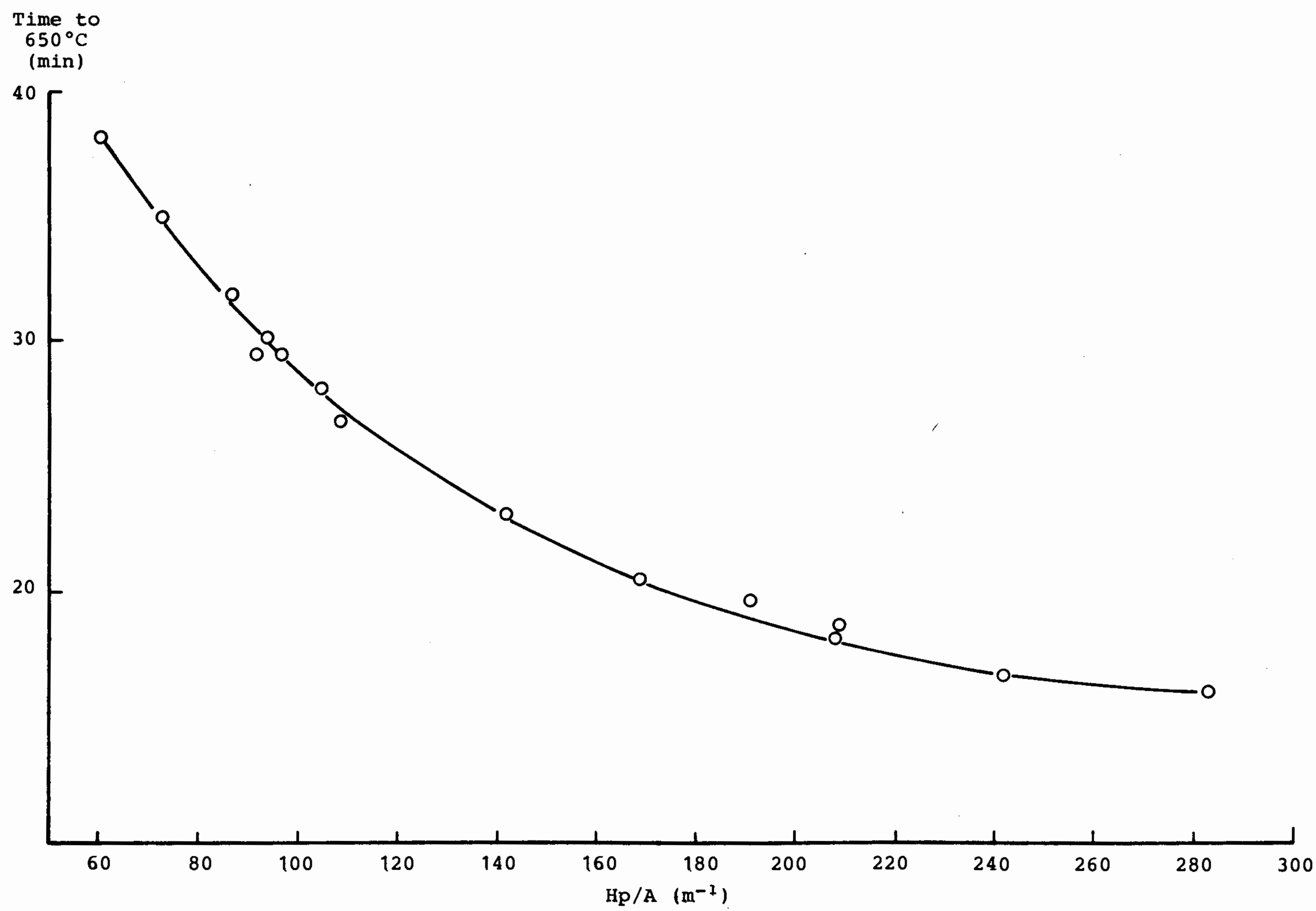
DIAGRAM OF STANDARD FIRE RESISTANCE BEAM TEST

FIG. 1
(R2/6854)



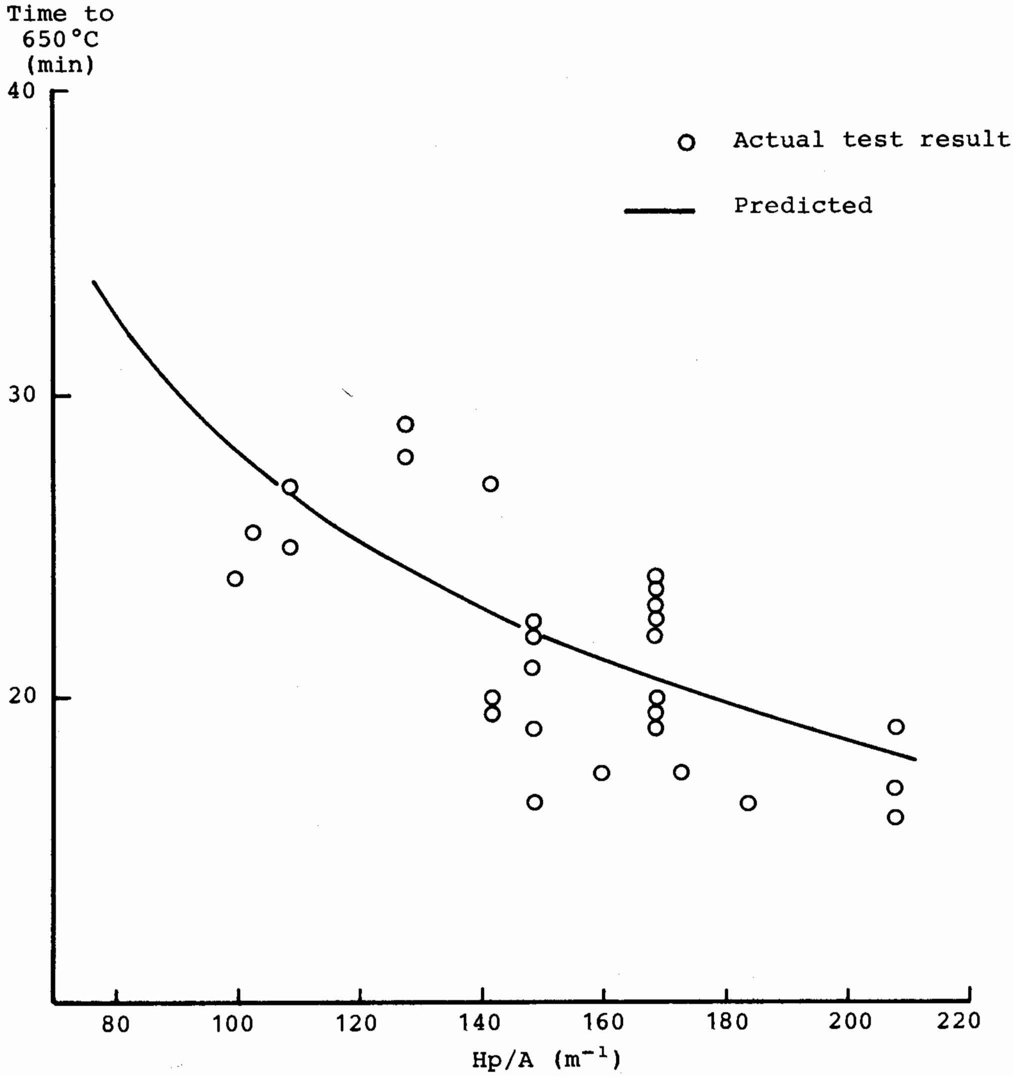
EFFECT OF SECTION FACTOR ON THE TIME
FOR THE LOWER FLANGE TO REACH 650°C
IN A BS476:PART 8 FIRE TEST

FIG. 2
(R2/6855)



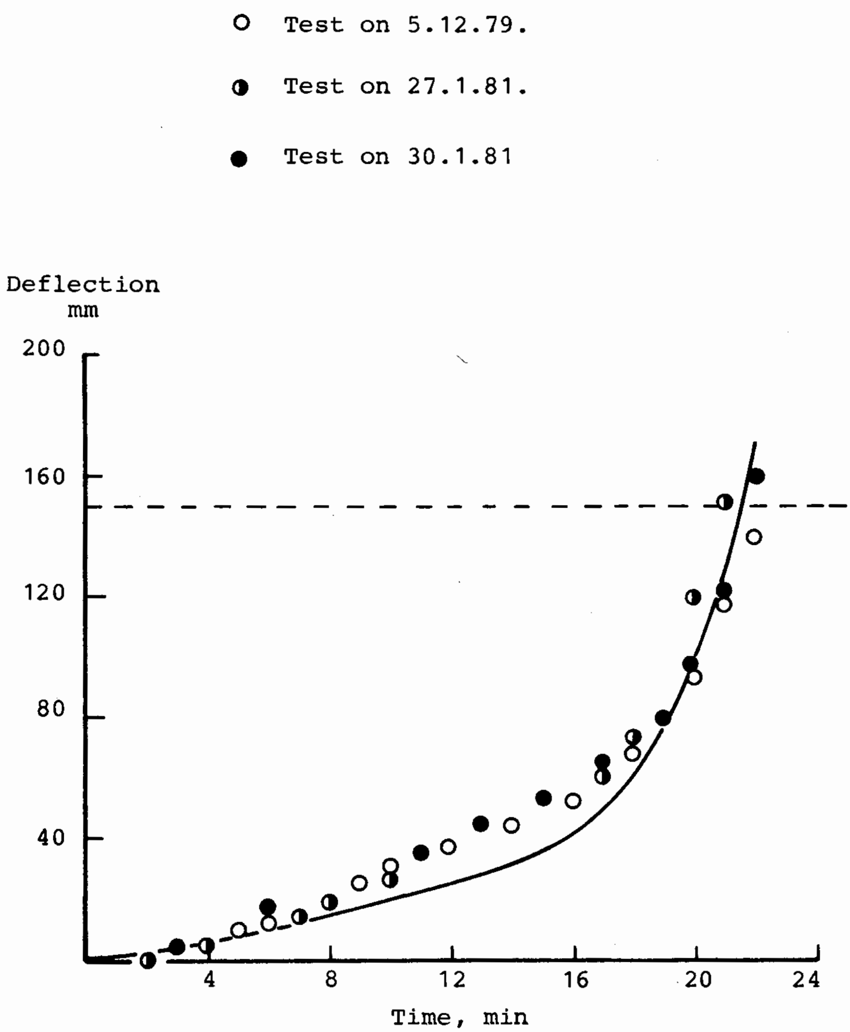
EFFECT OF SECTION FACTOR ON THE PREDICTED TIME FOR THE LOWER FLANGE OF A BARE STEEL BEAM TO REACH 650°C IN THE BS476:PART 8 FIRE RESISTANCE TEST MODEL
(SPAN = 4.5 m)

FIG. 3
(R2/6856)



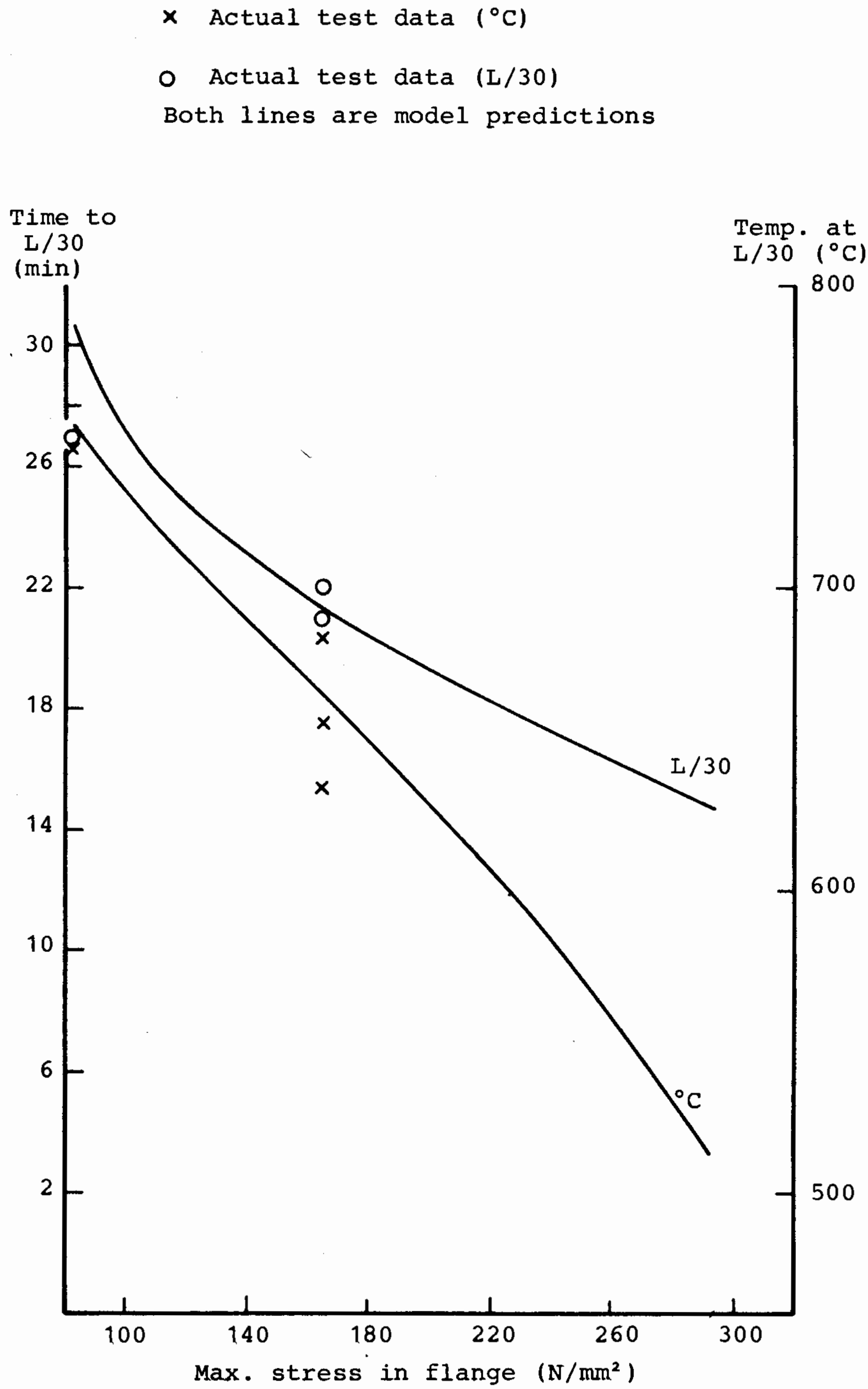
<u>COMPARISON OF PREDICTED WITH ACTUAL HEATING RATE DATA FOR BARE BEAMS (SPAN = 4.5 m) IN THE BS476:PART 8 STANDARD FIRE RESISTANCE TEST</u>

FIG. 4
(R2/6857)



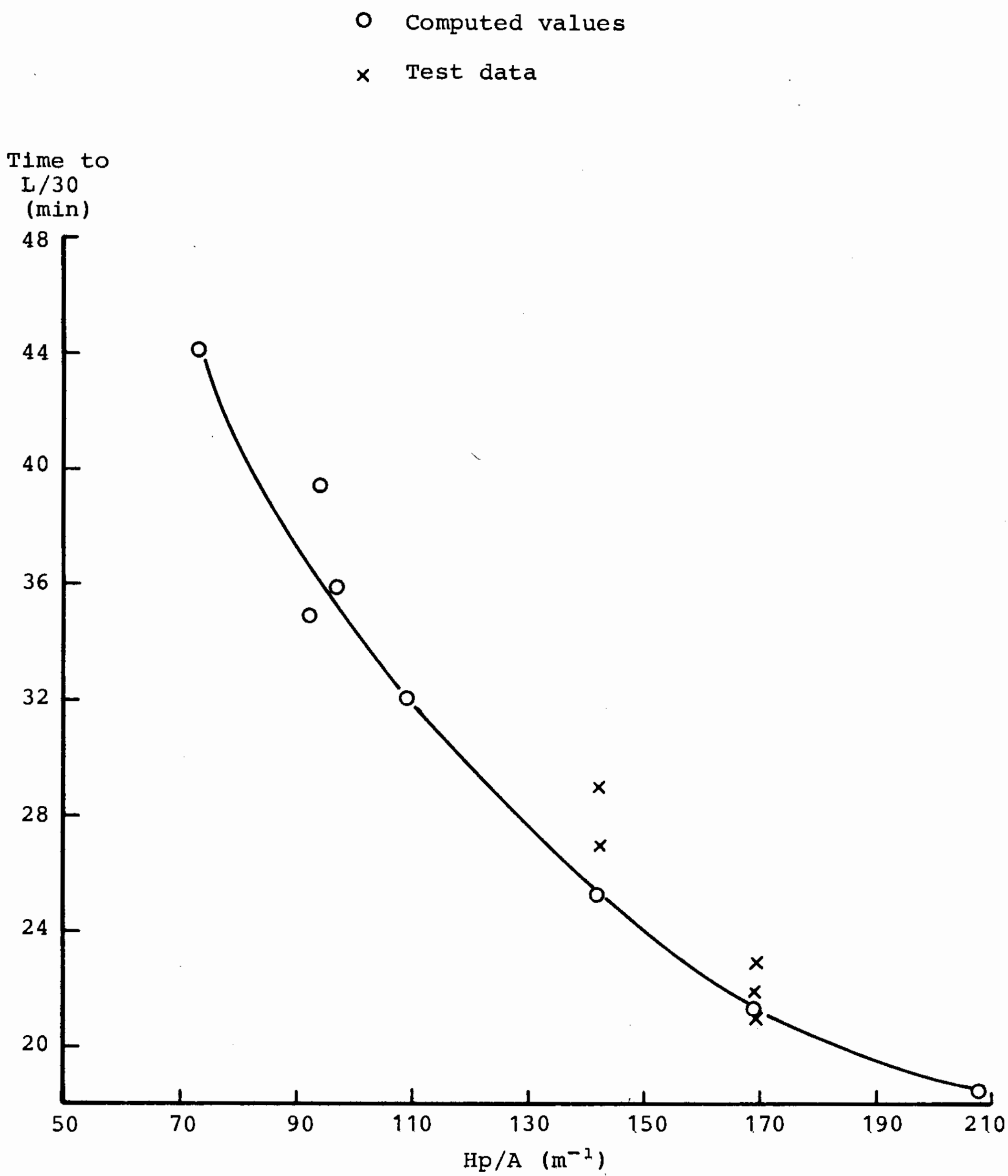
COMPARISON OF FIRE TEST DATA WITH CURVE
PREDICTED BY MATHEMATICAL MODEL. 254 x 146 mm x 43 kg/m
BEAMS IN SIMPLY SUPPORTED CONDITION OVER A 4.5 m SPAN

FIG. 5
(R2/6858)



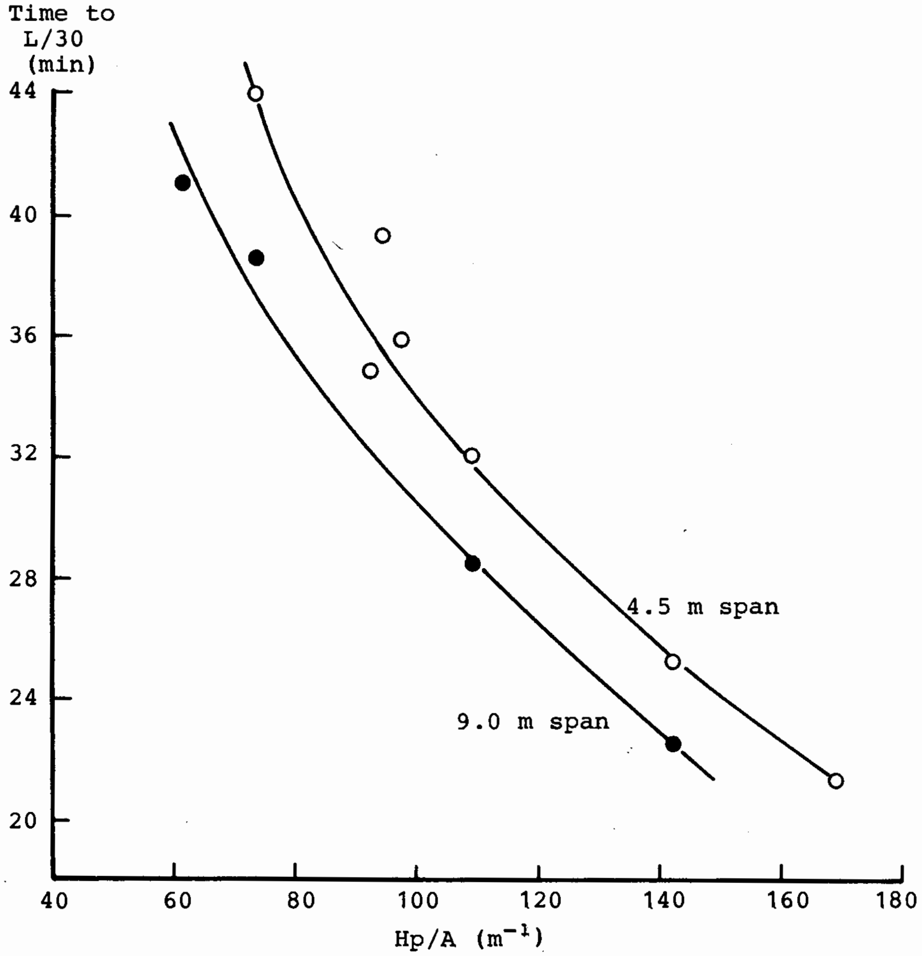
EFFECT OF DESIGN STRESS ON FIRE RESISTANCE TIME AND LIMITING TEMPERATURE OF SIMPLY SUPPORTED 254 x 146 mm x 43 kg/m BARE STEEL BEAMS IN BS476:PART 8 TEST, 4.5 m SPAN

FIG. 6
(R2/6859)



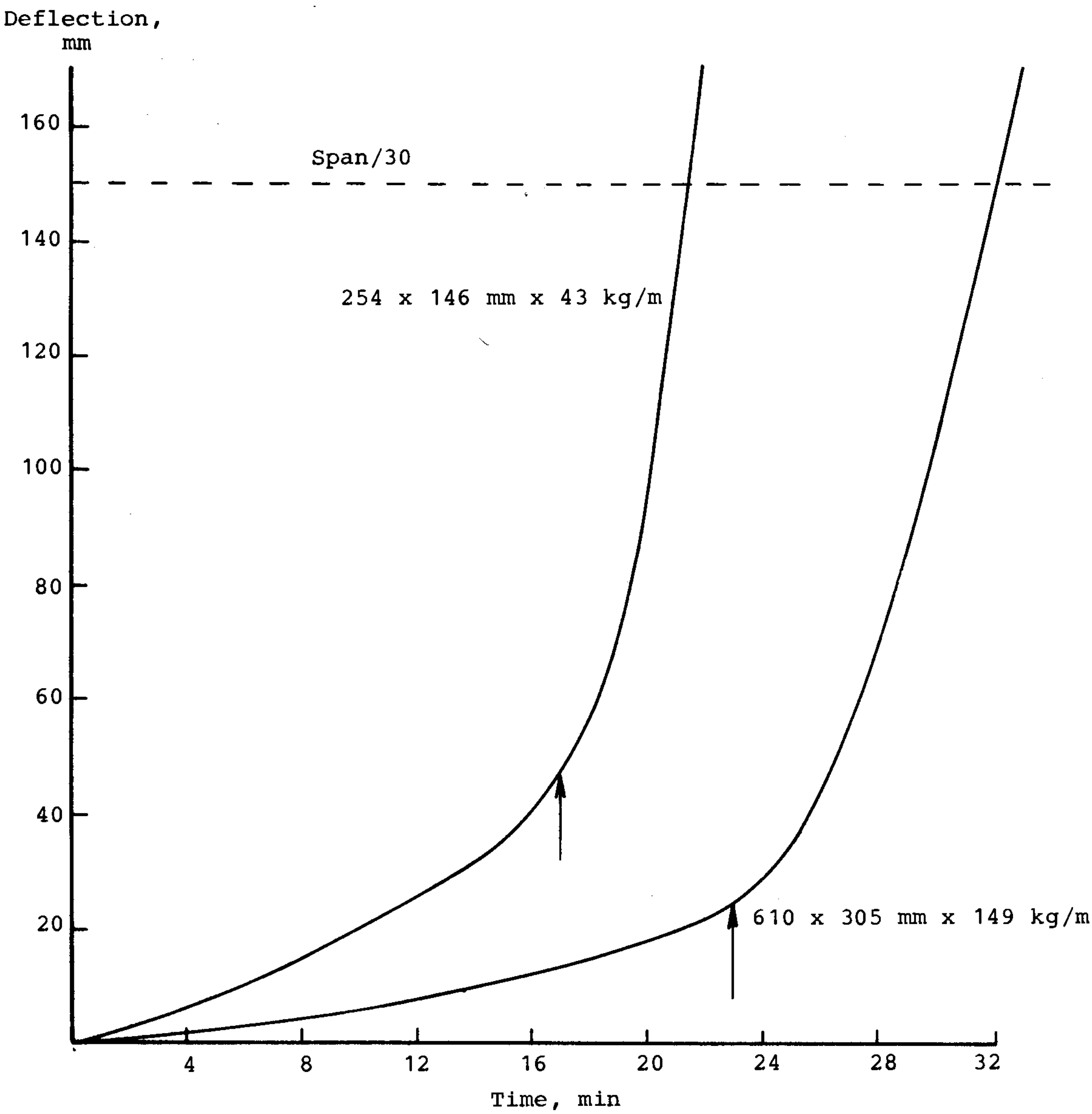
EFFECT OF SECTION FACTOR ON THE FIRE RESISTANCE TIME OF BARE STEEL BEAMS (SPAN = 4.5 m)

FIG. 7
(R2/6860)



EFFECT OF SECTION FACTOR AND SPAN ON THE FIRE RESISTANCE TIME OF BARE STEEL BEAMS

FIG. 8
(R2/6861)



PREDICTED DEFLECTION/TIME CURVES FOR TWO BARE STEEL BEAMS, STRESSED TO 165 N/mm², IN A BS476:PART 8 FIRE RESISTANCE TEST. ARROWS INDICATE POINTS AT WHICH RATE OF DEFLECTION EXCEEDS $L^2/9000d$

FIG. 9
(R2/6862)

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