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JOINT INDUSTRY SPONSORED RESEARCH:
THE FIRE RESISTANCE OF COMPOSITE BEAMS WITH UNFILLED VOIDS

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FOREWORD

The research leading to this report was funded by a number of organisations notably: fire protection suppliers and manufacturers, composite deck manufacturers, British Steel and others active in the design and construction of steel buildings.

The tests were designed by the Steel Construction Institute (SCI) and the tests were carried out by Warrington Fire Research Centre. British Steel (Swinden Labs) were responsible for manufacture and monitoring of the tests.

The report was prepared by G M Newman assisted by R M Lawson, and analysis of the tests was carried out by G M Newman and K F Chung.

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SUMMARY

Four fire tests have been carried out on composite beams. These beams were of a similar cross-section, and the principle variable was the form of fire protection. The 'control' test was a composite beam with a board type fire protection designed for a 'target' fire resistance of 60 minutes. In this test the voids created between the trapezoidal deck profile and the upper flange of the beam were filled. In the three further tests board, spray and intumescent coating were applied respectively, but in these cases the voids were left unfilled.

Load applied to the beams was equivalent to a test moment of 66% of the moment capacity of the composite section, taking into account the influence of partial shear connection and measured material properties. The test results are expressed in terms of limiting temperature of the lower flange. These limiting temperatures are higher than those of an equivalent non-composite beam for the same proportionate loading. The reduction in limiting temperature of the beams with unfilled voids relative to the same beams with filled voids is between 20°C and 60°C.

On the basis of these tests and their subsequent analysis it is proposed that for up to 60 minutes fire resistance no increase in fire protection is required for board and cementitious spray but for thin film intumescent coatings a small increase in protection thickness is required. This increase is not because intumescent coatings are inherently worse at fire protecting steel but because they are generally assessed using a higher steel temperature. For 90 minutes fire resistance the fire protection thickness must be increased for all materials. Detailed recommendations for fire protecting composite beams are given in the report.

1. INTRODUCTION

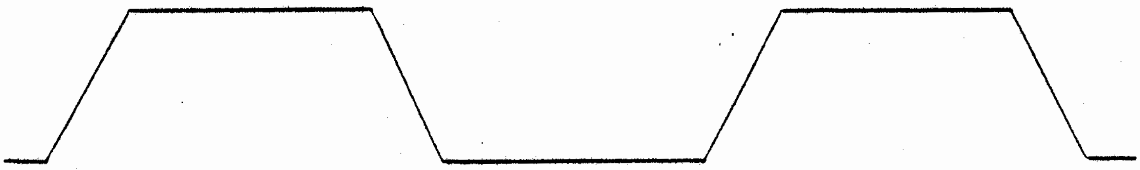
Most modern multi-storey steel framed buildings in the UK use composite construction for both the floor slab and the floor beams. A lightly reinforced concrete topping is designed to act compositely with a profiled steel deck to form the floor slab. The floor slab is then designed to act compositely with the steel beams to form "composite beams". Typically overall slab depths are about 130 mm and beams are spaced at 3 metre centres.

Two types of deck profile are used. These are the re-entrant dovetail deck and the open trapezoidal deck. Currently there are 4 proprietary types of dovetail deck and 8 types of open trapezoidal deck. Within each category differences in performance are small. The two types of deck are illustrated in Figure 1 and a schematic of a composite slab and beam system is illustrated in Figure 2.

The performance of composite slabs in fire is well understood. In recent years numerous fire resistance tests have been carried out and some of these tests are summarised in Table 1. Recommendations for the fire resistance of composite slabs have been published by SCI (1). It is usual to use composite slabs without any soffit fire protection. In fire the steel deck is largely sacrificial and the reinforcement acts to resist the moments acting on the slab.

Steel beams require fire protection for the fire resistance periods normally specified in buildings. Traditionally the amount of fire protection required has been based on tests using non-composite beams. Information on the use of fire protection materials is published in the "Yellow Book" (2). Generally the data given in this reference is based upon a steel failure temperature of 550°C for board and sprayed insulating materials and 620°C for thin film intumescent coatings. In applying fire protection to composite beams it is normal practice to fill the void formed between the profiled steel deck and the top flange of the beam with non-combustible material. With spray applied material this would normally be the spray material itself but with 'board' type fire protection other, more flexible, materials are often used.

For dovetail decks SCI have recommended (1) that it is not necessary to fill the small voids formed by the deck profile. This recommendation was based on observed behaviour in fire tests on unloaded beams.



Open trapezoidal steel deck

Re-entrant dovetail steel deck

Figure 1. Types of profiled steel deck

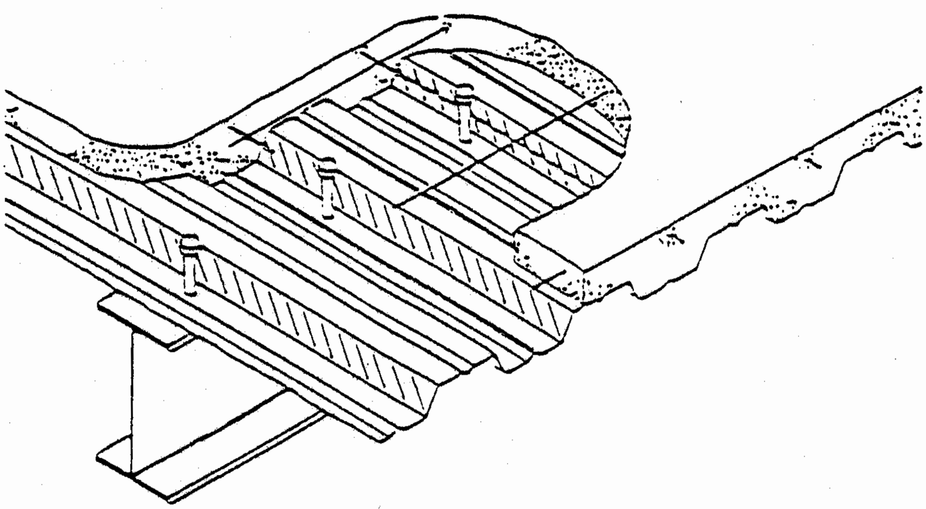


Figure 2. Principal components of a composite floor

Profile	Concrete type	Slab depth (mm)	Span (m)	Imposed load (kN/m²)	Reinforcement	Surface temp. (C)		Test period (min)	Test ref.
						After 1h	After 1½h		
Robertson QL59	LWC	130	3.0s	6.7	A142 mesh	73	-	60	CIRIA 1
Roberton QL59	LWC	130	3.0c*	6.7	A142 mesh	70	100	105	CIRIA 2
Robertson QL59	LWC	130	3.0c	6.7	A142 mesh	95	110	90	CIRIA 3
Holorib (UK)	LWC	120	3.0c*	6.7	A142 mesh	60	100	90	CIRIA 4
PMF CF46	LWC	110	3.0c	5.25	Y5@225 as mesh	110	135	101	FRS-BS1
Holorib (UK)	LWC	100	3.0c	5.75	Y5@150 as mesh	90	120	87	FRS-BS2
PMF CF46	NWC	135	3.0c	6.75	Y5@225 as mesh	85	95	120 (136)	FRS-BS3
Robertson QL59	NWC	140	3.6c*	6.7	A193 mesh	66	98	90	CIRIA 5
Metecno A55	NWC	140	3.6c*	6.7	A193	65	95	90	CIRIA 6
Holorib (UK)	LWC	150	3.0c*	10.0	A193	45	61	120	R.LEES 1
Ribdeck 60	LWC	140	3.0c*	5.6	A193	64	93	136	R.LEES 2
Ribdeck 60	LWC	140	3.0c*	8.5	A252	56	77	149	R.LEES 3

The tests are in chronological sequence from July 1983 until July 1989
+ failed prematurely because of loss of protection to beams
* test on long span/short span configuration

TABLE 1: SUMMARY OF UK FIRE TESTS ON COMPOSITE SLABS

However, for trapezoidal decks, no relaxation on void-filling was made because of the effect of the increased rate of heating of the partially protected steel section. This has severe economic disadvantages because void-filling is very labour intensive and mitigates against the use of trapezoidal decks with board-type fire protection.

Although the use of composite beams is very common no fire resistance tests on composite beams with profiled steel decking have been carried out in the UK or Europe. Tests have been carried out in North America and some studies on composite beams have taken place in Australia.

Recently, engineers specializing in structural performance have developed methods for mathematically modelling structures in fire. Using these methods it can be shown that the possibility exists with composite beams to leave the voids unfilled. The loss of strength caused by additional heating of the top flange is appreciably lower in a composite beam compared with a non-composite beam. This is because the top flange is close to the neutral axis of the section and contributes little to the overall bending capacity. In Table 2 a comparison of variation of moment capacity with top flange temperature is given for a composite beam and a similar non-composite beam. It can be seen that as the top flange temperature increases the non-composite beam loses strength at a much faster rate than the composite beam.

	Top Flange Temperature (°C)				
	300	400	500	600	700
Composite	100%	99.6%	96.7%	91.7%	87.5%
Non-composite	100%	99.6%	94.8%	80.0%	61.6%

NOTE: Bottom flange and web temperature assumed to be 600°C in every case

Data for illustrative purposes only.

TABLE 2 VARIATION IN MOMENT CAPACITY WITH TOP FLANGE TEMPERATURE

The purpose of the present research is to study the behaviour of composite beams in fire and to quantify the effect of not filling the voids formed with open trapezoidal decks. Three common forms of fire protection were considered, board, vermiculite cement spray and thin film intumescent coating. The actual products tested are considered by SCI to be typical of their type and the results of the research are considered to apply to all similar products.

2. DESIGN OF COMPOSITE BEAMS

The design of composite beams is to BS5950: Part 3 (3). This code has only recently been published and an SCI design guide (4) which was based on the expected requirements of the code, was published in 1989.

The design of composite beams is more complicated than steel beams as several different criteria have to be considered. Beams have to be checked under construction conditions when the steel beam supports the weight of wet concrete, under ultimate limit state conditions when the composite beam supports the factored dead and imposed loads and under serviceability limit state conditions when the effect of normal working loads is considered. In many practical designs the bending capacity of the composite section will not be the governing criteria, ie. serviceability stress, minimum shear connection or deflection may govern.

Therefore it will often be the case that capacity of the section will only be 90% utilised. This will result in the load ratio at the fire limit state being less than a similar non-composite beam. The concept of load ratio is introduced in BS5950: Part 8 (5) and is discussed later.

An important feature of the design of composite beams is the shear connection provided between the steel beam and the concrete compression flange. The effect of different degrees of shear connection is illustrated in Figure 3. Clearly if no shear connectors are provided the moment capacity is simply the capacity of the steel beam alone. As the number of shear connectors increases composite action takes place and an increased moment capacity is obtained. If sufficient connectors are provided the maximum moment capacity of the section is reached. This is normally called 100% (or full) shear connection. BS 5950: Part 3 states that at least 40% shear connection must be provided.

Designers may select the degree of shear connection that they require in any particular design situation provided they are within the limits specified by the code. Shear connection is very important when considering fire. For normal design the capacity of the shear connectors will often be the limiting factor ie. the capacities of the steel beams and the concrete slab will both be greater than that provided by the shear connectors. In fire the limiting factor will depend upon the relative loss in strength of the heated beam and the shear connectors. If the beam loses strength at a faster rate the degree of shear connection will increase and failure will depend upon the 100% shear connection moment capacity regardless of the degree of shear connection provided. In the event the performance of the shear connectors was found to be critical in cases where the top flange temperature was high. This is further discussed in Section 7.

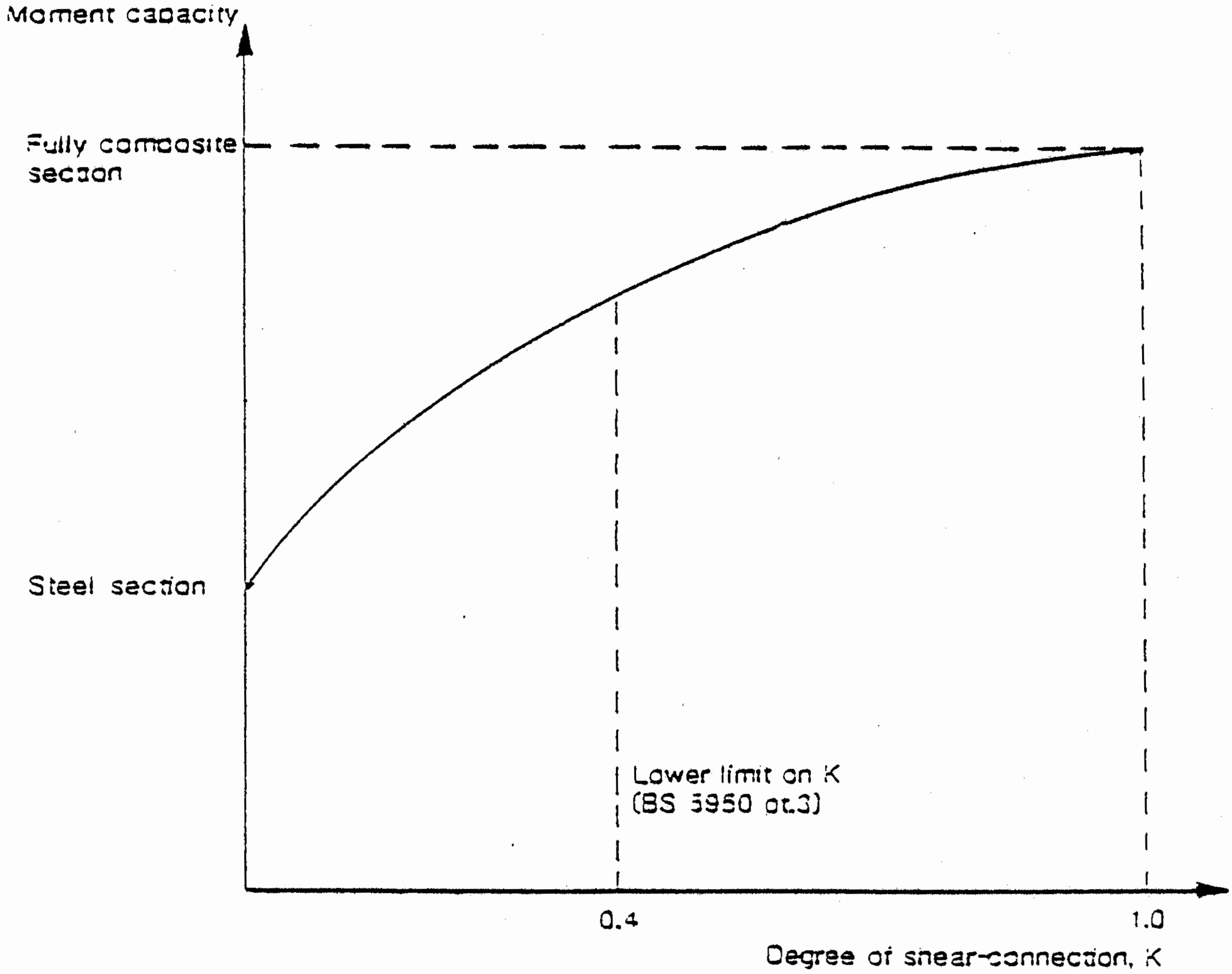


Figure 3. Effect of degree of shear connection on moment capacity

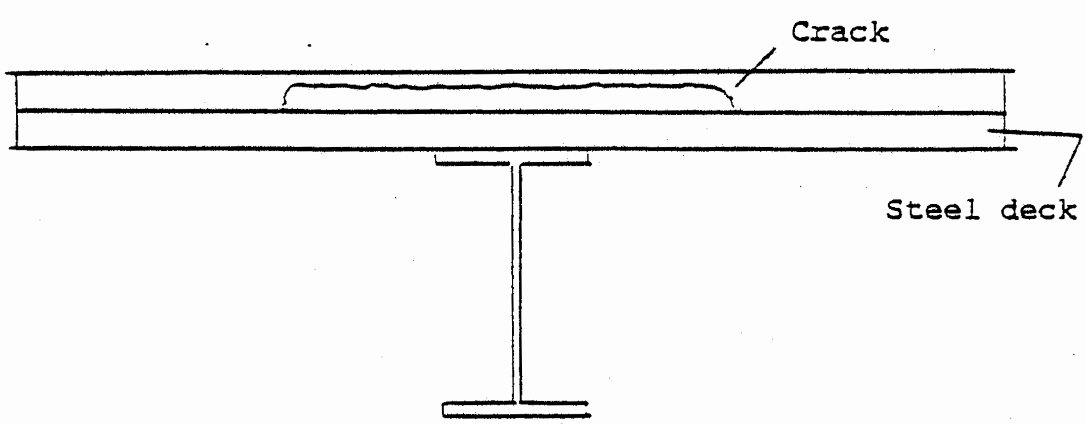


Figure 4. Cracking of concrete at end of beam

3. BS5950: PART 8

BS5950: Part 8, Code of Practice for Fire Resistant Design gives two methods for calculating the load capacity of beams in fire. They are the limiting temperature/load ratio method and the moment capacity method.

3.1 Limiting Temperature Method

In a fire resistance test on a steel member the temperature of the critical element (normally the exposed flange) of the steel section at the point of structural failure is dependent on the load that the member supports. The analysis of numerous fire tests has shown that with steel beams the load at time of failure can be directly related to the temperature of the bottom flange. If the load is expressed as the fraction of the 'cold' capacity the beam it has been found that all beams can have their performance in fire expressed in terms of a certain limiting temperature for a given load ratio. The load ratio is defined as:

$$\text{Load ratio} = \frac{\text{Load or moment at the fire limit state}}{\text{Load or moment capacity at } 20^{\circ}\text{C}}$$

Load Ratio	0.2	0.3	0.4	0.5	0.6	0.7
Limiting temperature	780	725	680	650	620	590

Table 3 Limiting temperature for beams supporting concrete floors (°C)

For non-composite beams and composite beams protected with fire protection materials which have demonstrated their 'stickability' or ability to remain intact in fire, the relationship between limiting temperature and load ratio is given in Table 3.

In calculating the load at the fire limit state Part 8 permits a partial factor of 0.8 to be used for non-permanent loads and a factor of 1.0 for permanent loads. If it is assumed that the dead and imposed loads are in the proportion of 1 to 2 then the load ratio in fire is given by:

$$R = \frac{1 + 2 \times 0.8}{1.4 + 2 \times 1.6} = 0.56$$

The values of 1.4 and 1.6 are the load factors used for dead loads and imposed loads for normal design.

If the bending capacity is not fully utilised, say to 90%, the load ratio would reduce to 0.5. Thus the limiting temperature would be approximately 650°C.

In calculating the load ratio the moment capacity at normal temperature is clearly important. Strictly, following the definition of load ratio one should use the actual moment capacity taking into account the degree of shear connection under normal conditions. However the moment capacity in fire is largely independent of shear connection. Any design recommendations for composite beams in fire are therefore dependent on the degree of shear connection present under normal conditions.

3.2 Moment Capacity Method

If the temperature distribution across a section is known then it is possible to calculate the moment capacity of the beam. Part 8 introduces this method for steel beams and illustrates the method for a shelf angle floor beam. It gives no guidance on the use of the method for composite beams but SCI have extended the guidance given in the Code for composite beams. In principle, if the temperature distribution through the section is known, then the reduced strength of all the elements in the cross-section can be calculated. The plastic neutral axis and, hence, the moment capacity in fire conditions can then be determined directly.

4. SUMMARY OF EXISTING TEST DATA

4.1 British Steel tests on loaded beams

In March 1981 British Steel carried out two fire resistance tests on composite beams. These are reported in Compendium of UK Standard Fire Test Data (6).

In the first of the tests (British Steel reference 15) a composite beam, not utilizing profiled steel decking, and loaded as if it was a non-composite beam, reached a deflection of span/30 after 35 minutes and was on the verge of failure after 40 minutes. In the second test (ref. 16) a similar beam loaded as a composite beam, reached deflection of span/30 after 22 minutes and was at this stage rapidly approaching failure.

These tests have been analysed using the moment capacity method (MCAP) noted in Section 3.2. The results are summarised in Table 4.

	Flange temp		Moment kNm			Load Ratio	
	Top	Bottom	Test	MCAP	Capacity	Test	MCAP
Ref. 15	606	762	79.3	74.4	279.0	0.284	0.267
Ref. 16	469	654	147	140.9	272.3	0.540	0.517

Table 4 Comparison of British Steel fire resistance tests on composite beams and the moment capacity method.

It can be seen that the moment capacity method (MCAP) is reasonably accurate and conservative in both cases. The limiting temperatures of the bottom flange agree well with the load ratio approach given in Table 3.

4.2 Temperatures measured in fire protected composite beams

In two recent test programmes temperatures on unloaded fire protected composite beams were measured. These are summarised in Table 5. A feature of the tests was the measurement of top flange temperatures at positions where the void between the steel deck and the top flange of the beam was not filled with any fire protection material. The tests considered two generic deck shapes typical of those marketed in the UK: the dovetail profile, Holorib and the open trapezoidal profile as represented by PMF CF46 and Ribdeck. In the PMF and Holorib tests sprayed fire protection was carefully removed from the voids whilst maintaining protection to the flange tips. In the Ribdeck test board protection was used.

It can be seen that with Holorib, the effect of not filling the voids is negligible. However, with the open trapezoidal profiles, the effect of not filling the voids is pronounced. Ribdeck has larger openings than PMF CF46 and temperatures at unfilled void positions were between 60 and 113°C greater after 105 minutes. Temperatures are compared with those measured in this research programme in Section 6.

	PMF LWC			PMF NWC			Holorib LWC			Holorib NWC			Ribdeck LWC		
	B	TF	TU	B	TF	TU	B	TF	TU	B	TF	TU	B	TF	TU
30	135	103	188	107	90	175	100	104	124	130	125	116	87	-	315
60	312	218	346	266	170	316	238	195	225	302	238	216	208	-	427
90	489	335	487	435	275	447	411	302	333	480	347	327	385	-	562
105	563	389	551	510	326	504	488	346	383	555	398	379	458	-	617
120	-	-	-	-	-	-	-	-	-	-	-	-	534		671

Table 5 Temperatures measured in composite beams using profiled steel decking (°C)

Notes:

Decking: PMF CF46, Super Holorib Slab thickness 120mm
Beam size 406 x 178 x 60
Decking: Ribdeck 60 Slab thickness 140 mm Beam size 305 x 165 x 40
LWC: Light weight concrete (density 1850 kg/m³) NWC: Normal weight concrete
B: Bottom flange TF: Top flange, filled voids TU: Top flange, unfilled voids

5. TEST PROGRAMME ON COMPOSITE BEAMS

This test programme had the objective of understanding the behaviour of composite beams with profiled decking in fire conditions, and of quantifying the effect of not filling the voids above the top flange of the beam on the limiting temperatures of the beams.

Following discussions with sponsors it was decided that the minimum viable programme would be to carry out four fire resistance tests using three types of fire protection. The first test would act as a control and would have filled voids and the other tests would be carried out with unfilled voids.

The three types of fire protection selected were:

a. Dry board
b. Cementitious spray
c. Thin film intumescent coating.

Products were selected by SCI as being typical of their type so that the results obtained could be applied to all similar materials. It was recognised that differences would not effect the comparative performance on composite beams with filled or unfilled voids.

The suppliers of the selected materials were asked to apply sufficient fire protection to keep the bottom flange temperature below 600°C after 60 minutes. The precise performance was not considered to be critical as it was intended to continue the period of heating beyond structural failure up to 90 minutes. Provided the temperature history was obtained the structural performance could be calculated.

It was decided that the control test with filled voids, should be carried out using the board protection system. This was because the potential cost savings using board were considered to be higher than either of the other two systems. Ideally control tests are required for each system but this was not possible with the limited funding available.

In the test using cementitious spray only nominal cover to the edges of the top flange was provided. Clearly if the voids are to be left unfilled it is extremely difficult to spray the required thickness to the flange edge. When spraying the beam, the voids were masked off so that no spray was allowed to enter the voids. In practice this would never be achieved (or even attempted) so the test condition was very onerous. This comment applies also to the intumescent coating.

Structurally, a fire resistance test on a representative composite beam is not straight forward. Fire tests are normally carried out on a beam spanning 4.5 metres and composite beams typically have an overall span to depth ratio of about 20. With a slab depth of 125mm the beam would only be 100mm deep for this span. Also, it is normal to assume that the effective breadth of the slab is equal to ¼ of the span. It was decided that a 305 x 102 x 33 universal beam, grade 43A, should be tested to be representative of the proportions of composite beams in practice. The beam span for this section would be about 8m, and hence the effective breadth of the slab would be 2m. Hence, the loading on the beam was increased to maintain the same moment over 4.5m (the span of the test beam) as over 8m.

Grade 43 steel, as opposed to the more commonly used grade 50 was specified to reduce the strength of the beam compared to the strength of the concrete compression flange. The same size beam was used in each test and the loading was calculated to give a mid-span moment of 161.3 kNm. This represents 66% of the moment capacity of the beam calculated assuming partial shear connection and based on the measured material properties. The design calculations are given in Appendix F.

The shear connectors were placed in a regular pattern of one per trough, typical of modern practice. Because of the relatively short span, the number of shear connectors and hence the degree of shear connection were less than would be the case for a beam of this size. The degree of shear connection was calculated to be 37%.

The test programme was as follows:

Common Data

Beam	305 x 102 x 33 UB Grade 43
Span	4.5m
Slab depth	125mm
Deck depth	60 mm, open trapezoidal
Concrete	Normal weight, Grade 30
Shear Connectors	19mm diameter at 300 centres
Reinforcement	A142, 30mm top cover
Central Moment	161.3 kNm

Test 1

Control test
Dry board protection 18mm thick
Voids filled with shaped pieces of same board

Test 2

Dry board protection 18mm thick
Voids unfilled

Test 3

Cementitious spray 23mm thick (average)
Cover to edges to top flange 10mm
Voids unfilled

Test 4

Thin film intumescent 1.2mm thick (average)
Top flange not coated
Voids unfilled

The measured strength of the steel beams was 295N/mm^2 and the measured concrete strength (cube strength) was 55N/mm^2.

Thermocouples were fitted to the beams to enable the temperature at any point in the central region to later be estimated. In tests 3 and 4 a thermocouple was also placed at the centre of the central unfilled void.

6. OBSERVATIONS IN TESTS

6.1 Structural Performance

The structural performance of each test was similar. Up to approximately 80% of the eventual failure time, there was a gradual increase in deflection of approximately 1mm/minute. Beyond this point, the rate of deflection increased significantly until at failure, deflection rates of over 10mm/minute were recorded. This occurred at deflections exceeding span/30 but generally less than span/20.

The failure time is not itself critical to the assessment of the tests but for the record the load was removed at the following times:

Test 1:	68 minutes
Test 2:	61 minutes
Test 3:	74 minutes
Test 4:	51 minutes

Failure occurred by the tensile yielding of the steel section, although there was some evidence of concrete cracking indicating that longitudinal shear failure may have occurred on further heating (Figure 4). However no failure of the welds of the shear connectors occurred, despite the high top flange temperatures experienced. No loss of integrity of the slab occurred.

Tests 1, 2 and 3 failed in a similar, manner and there was no structural difference in the mode of failure. Cracking occurred in the manner shown in Figure 4 suggesting local failure of the concrete around the shear connectors at the ends of the span. The influence of not filling the deck voids contributed to a 13% reduction in fire resistance time. The better performance of test 3 in terms of failure partly arose from the slight over spraying (about 10%) relative to the specified protection thickness. However, more important is the temperatures at which failure occurred. This is discussed in the following section.

Test 4, comprising the thin film intumescent coating failed prematurely because of a local defect in the material leading to local over-heating of the bottom flange and web.

The failure occurred adjacent to a cover plate used to protect the thermocouple and probably there was some reduction in coating thickness at this point. Extremely high strains occurred locally, resulting in 'necking' and rupture of the flange. It was concluded that this was not representative of practice.

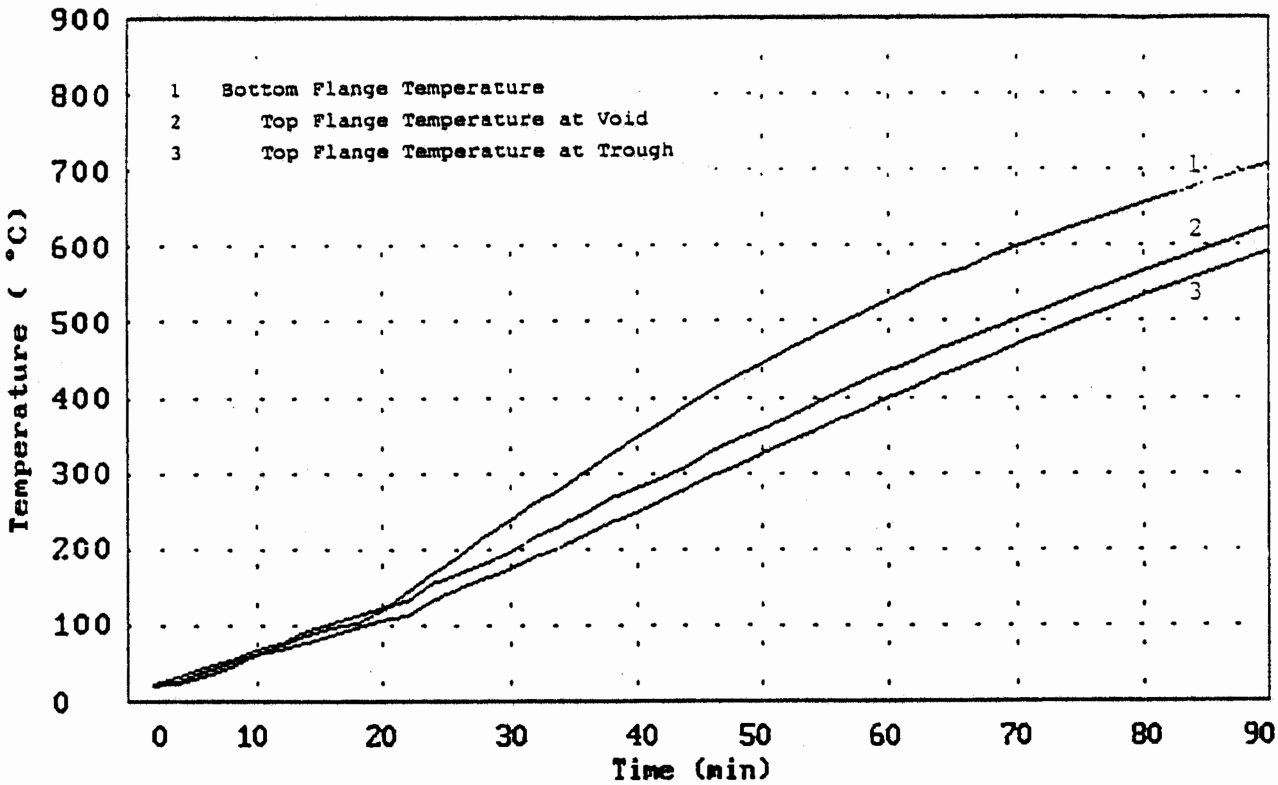


Figure 5. Temperatures recorded in Test 1

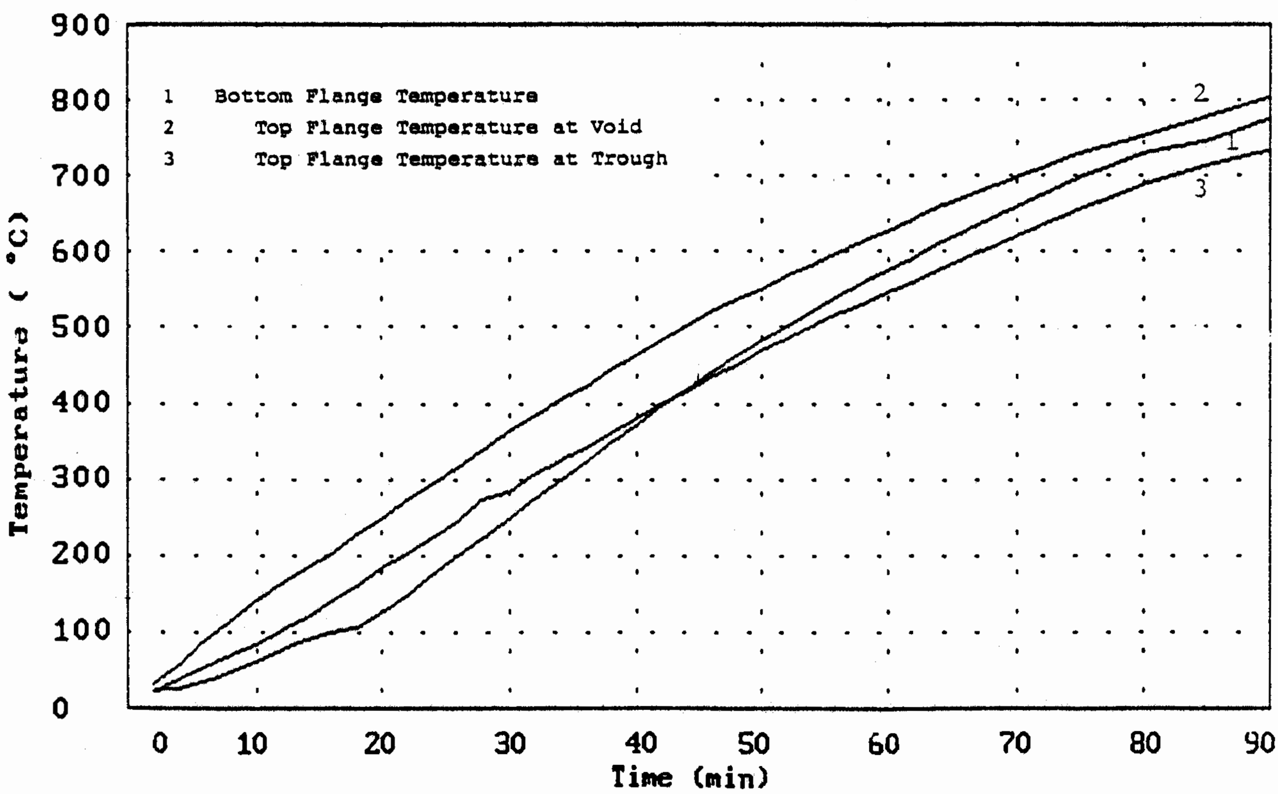


Figure 6. Temperatures recorded in Test 2

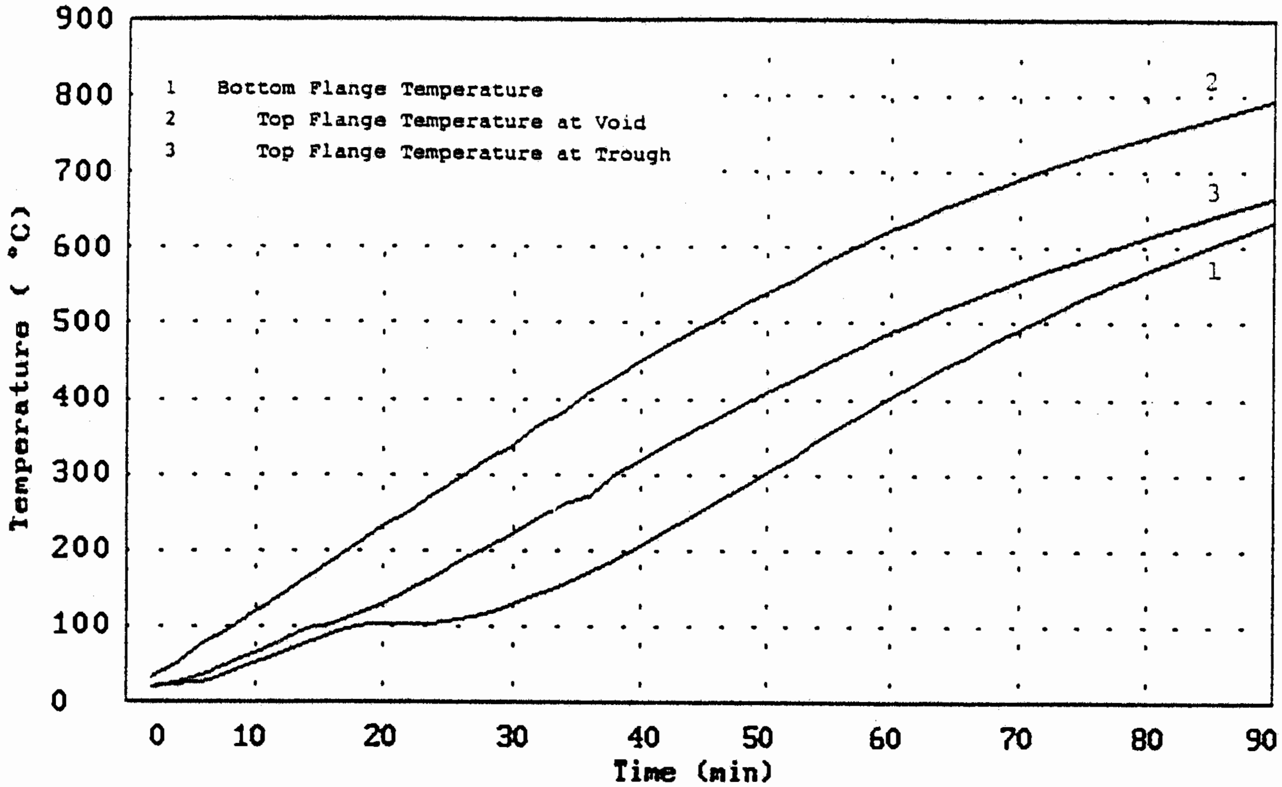


Figure 7. Temperatures recorded in Test 3

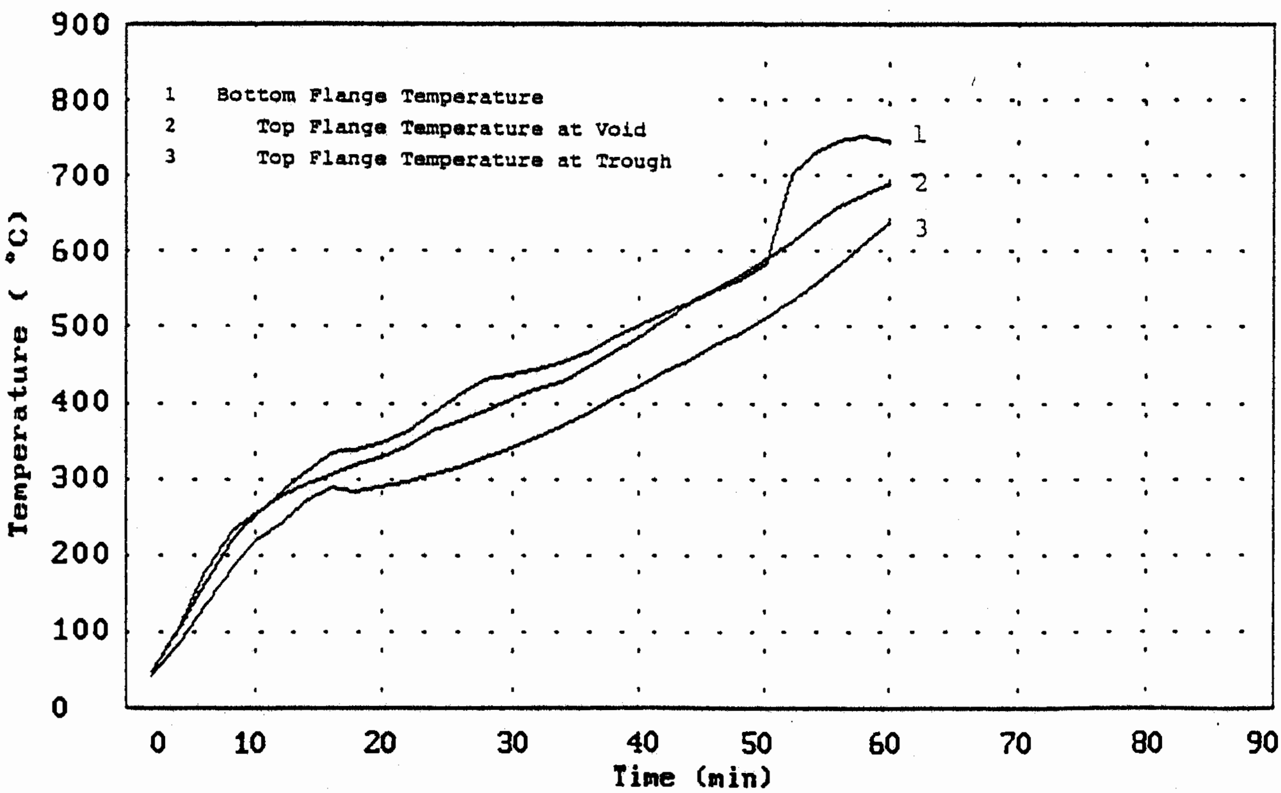


Figure 8. Temperatures recorded in Test 4

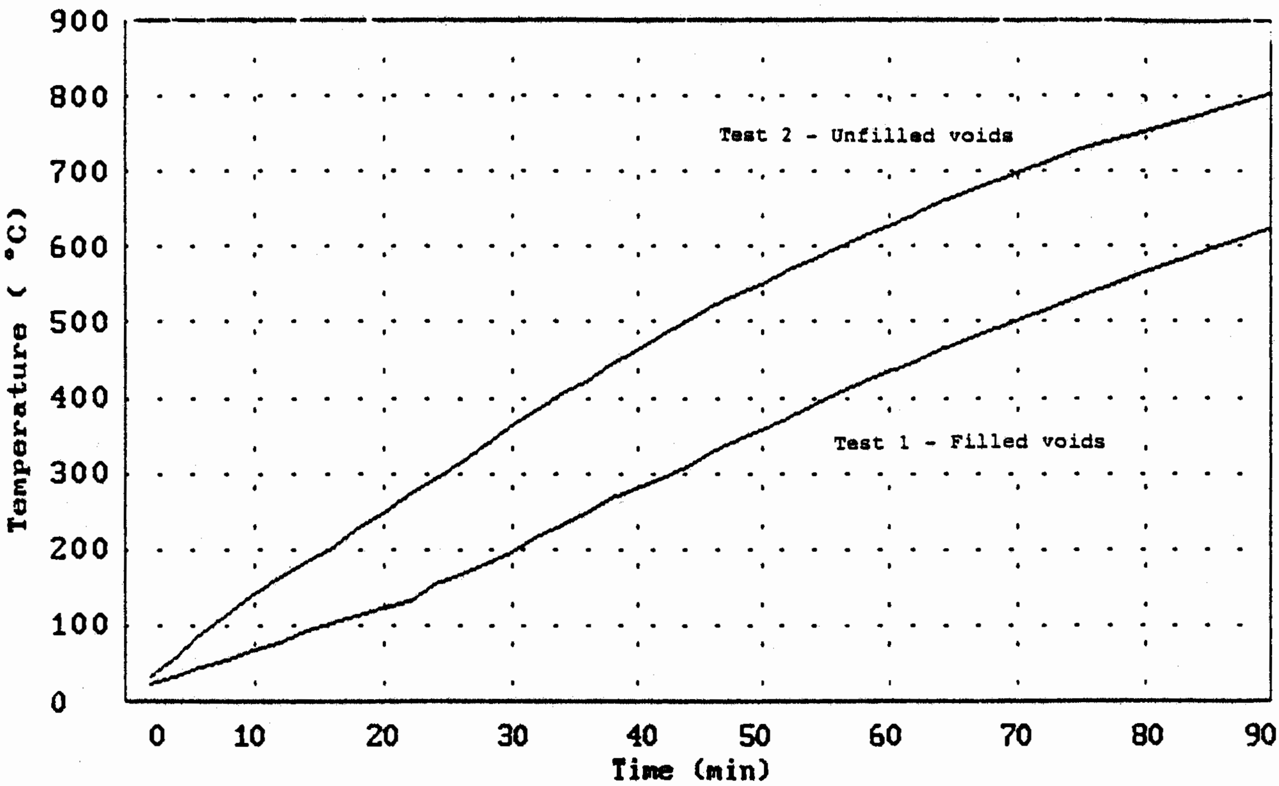


Figure 9. Comparison of top flange temperatures between Test 1 and Test 2

6.2 Thermal Performance

Measured temperatures for each test are given in Appendices B, C, D and E. The bottom flange temperatures at failure were respectively in the four tests 584, 583, 524 and 581°C. Apart from test 3 these results show remarkable consistency. Possible reasons for the low temperature in test 3 are discussed later. In Figure 5 to 9 the temperature data is plotted and various comparisons are illustrated. Before any detailed comparisons are made these figures refer to:

Temperature distribution in flanges

In each test the variation in temperature across the width of the top flange was very small. Recorded temperatures for various positions across the top flange are given in the Appendices.

Temperature variations in beams

The temperatures at various points on the cross section of the beams after 60 minutes for tests 1 to 3 and after 48 minutes for test 4 are summarised in Table 6. The time of 60 minutes is used for reference purposes, but the limiting temperatures of the section are obtained at the relevant failure time. Unfortunately, the last sensible temperature measurements in test 4 were recorded at 48 minutes.

For tests 1 and 2 in which board protection was used the variation in temperature over the lower half of the section is very small. In test 1, with filled voids, the temperature of the top flange at the solid trough position was 36°C lower than at the filled void position. This effect is still apparent at the ¼ web height position. The top flange was close to 100°C cooler than the bottom flange. In test 2, with unfilled voids, the temperature distribution at the unfilled void position is reasonably uniform with the top flange being 53°C hotter than the bottom flange.

The average temperature of the beam after 60 minutes in test 1 was about 500°C and that of test 2 about 580°C. This indicates that 18% more heat had entered the section in test 2 as a result of not filling the deck voids. However, structural performance is largely dependant on the temperature of the bottom flange and here the rate of temperature increase was only 9% in comparison to a 45% increase for the unprotected top flange.

In test 3, with cementitious spray protection, the bottom flange temperature was appreciably lower than the web temperatures. The top flange temperature at the unfilled void position was approximately the same as in test 2 but the temperature gradient at the top of the web was greater than that in test 2. As the difference in bottom flange temperature between tests 2 and 3 is very great it is clear that the beam in test 3 had an appreciably higher degree of insulation. Generally comparing test 2 with test 3 it can be seen that with the board protection, (test 2), the beam had a much more uniform temperature. This is almost certainly due to internal heat transfer across the internal voids formed by protection in the form of a box around the section.

The temperatures in test 4, with a thin intumescent coating, cannot readily be compared to the other tests. As a spray applied material the distribution is not similar to test 3. At the unfilled void position the temperature distribution is even. At the solid trough position it is apparent that for some reason the temperatures were greater than at the unfilled void position. The bottom flange was approximately 100°C hotter than the top flange with smaller increases up the web. The top flange temperature appears to be in line with the other test temperatures for unfilled voids. Throughout this test the bottom flange temperature at the central solid trough position was higher than at the void position and this difference became very large after 50 minutes. This would indicate a local weakness in the effectiveness of the coating.

Visual observations during the test and an examination of photographs taken before and during the test suggest that the intumescent coating was effected by the method of shielding of the thermocouple wires. A thin steel sheet was tack welded into the root of the beam and the thermocouple wires were placed in the void behind the sheet. At various points gaps were left for the thermocouple wires to pass through. It is thought that a 'hot spot' developed close to one of these gaps and caused premature failure. This type of fault would not occur in practice.

The temperatures recorded on the top flanges of the beams with unfilled voids were appreciably higher than those recorded in earlier tests (Table 5). This difference is thought to be caused by the position or orientation of the beams. In the earlier tests the beams were either transverse, across the furnace or were partially shielded. It is likely that heat transfer to the top flange is greatly affected by convention within the furnace.

Temperatures in shear connectors

Temperatures in the shear connectors (studs) were measured at their base and on the head. The recorded values are summarised in Table 7. In each test the base temperature is about 110 to 130°C lower than the corresponding flange temperature. The highest temperature at which the connectors were carrying an appreciable load occurred in test 3 with a base temperature of 466°C and a head temperature of 218°C. This position was reached after 74 minutes at which point the applied load was removed.

After 90 minutes the temperature at the base of a shear connector reached a maximum value of 594°C in test 2. This is significant when considering the possibility of shear connector performance being critical for 90 minutes fire resistance.

6.3 Deflections

The central deflections of the beams are presented in Figure 10 to 13. There is a close relationship between the rate of deflection over the first half of the test and the eventual failure time (compare tests 1 and 2). Some of the deflection is probably due to thermal bowing caused by temperature differences across the section, but towards the end of the test this is dominated by structural weakening of the section.

Test 4 behaved differently (see Figure 13) in that initially the thin film coating expanded (or intumesced) over a 10 minute period. This corresponds to a rapid increase in deflection. Then the beam deflection stabilized, but after 40 minutes the rate of deflection increased considerably.

Test	Time (Minutes)	Shear Stud Temperature (°C)	
		Head	Base
1	60 68 90	115 132 196	266 307 424
2	60 62 90	192 200 319	409 420 594
3	60 74 90	162 218 285	374 466 553
4	50 60	181 260	369 460

Table 7 Shear connector temperatures

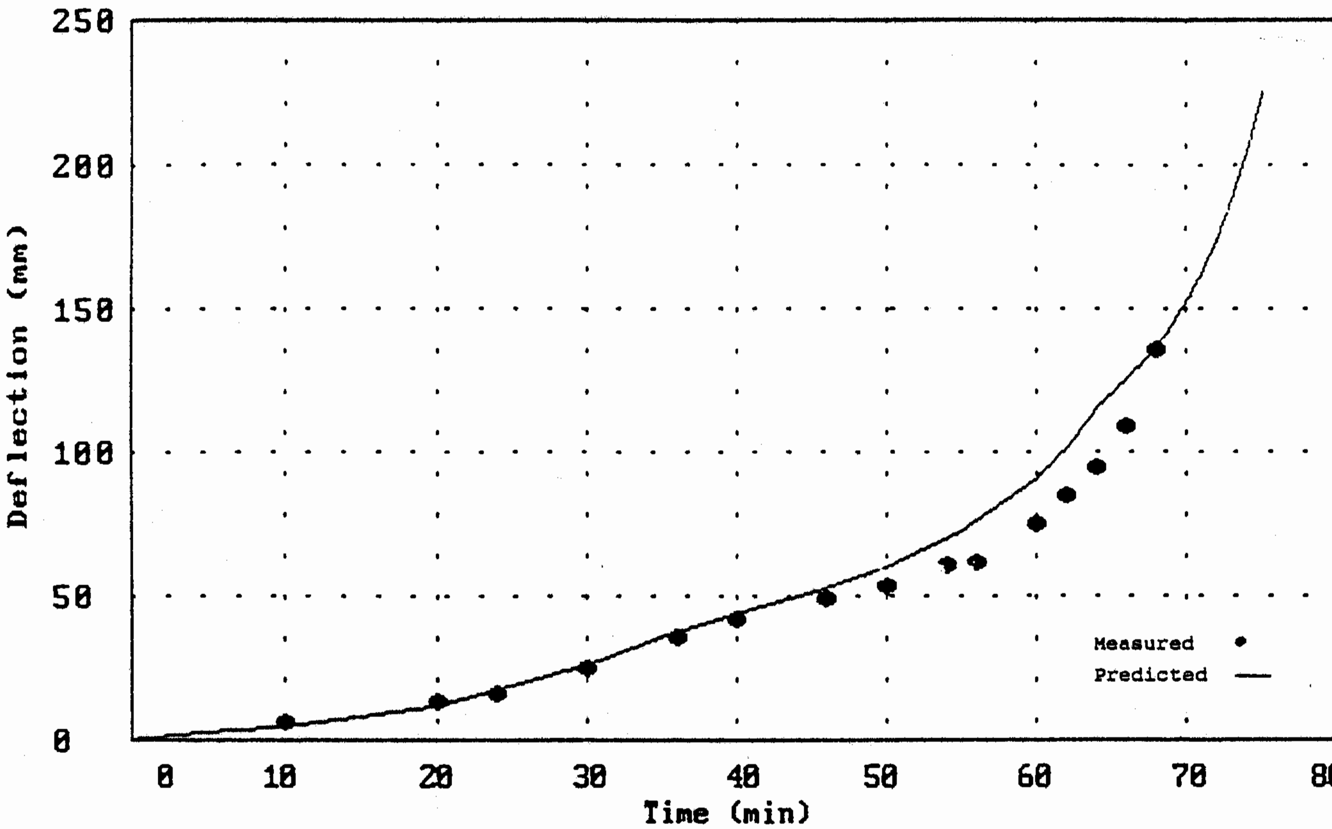


Figure 10. Measured and predicted temperatures

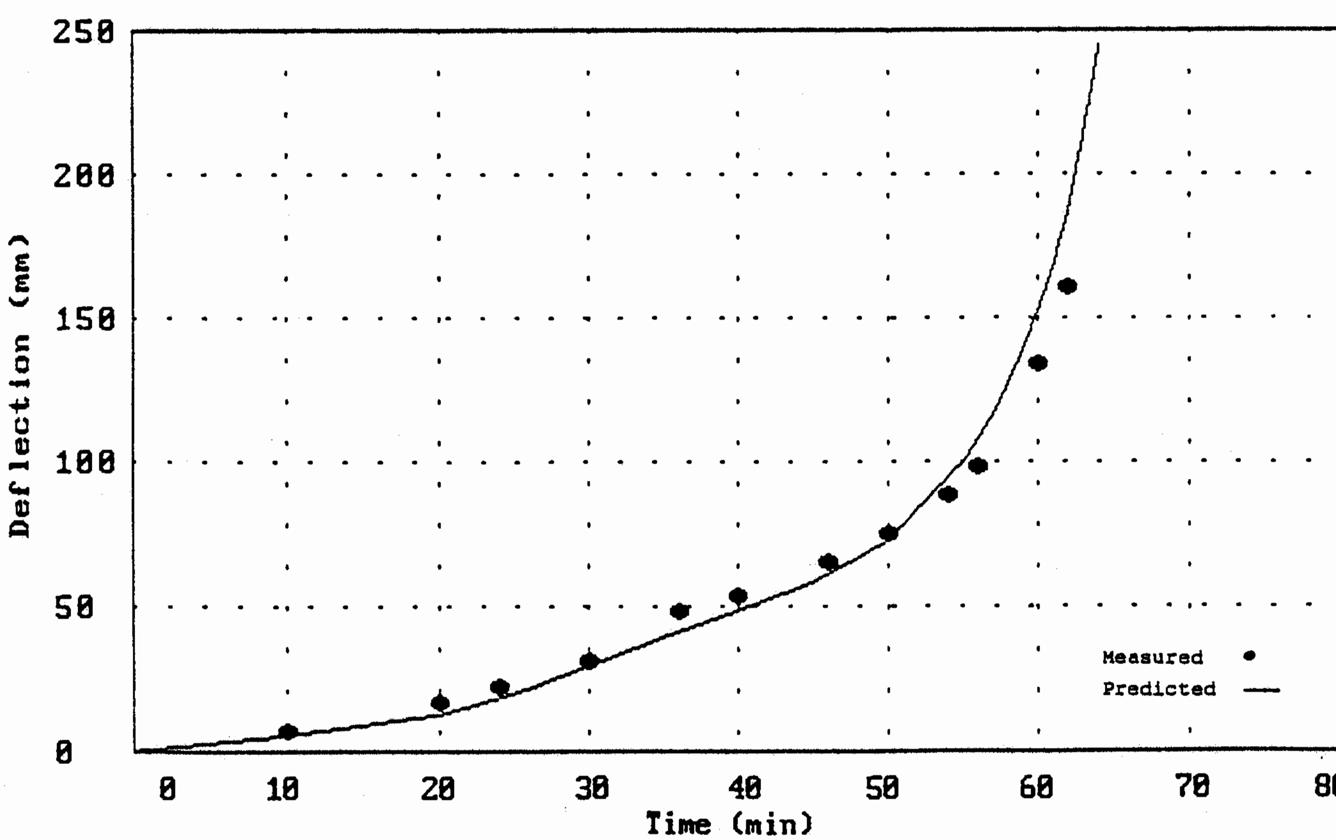


Figure 11. Measured and predicted temperatures in Test 2

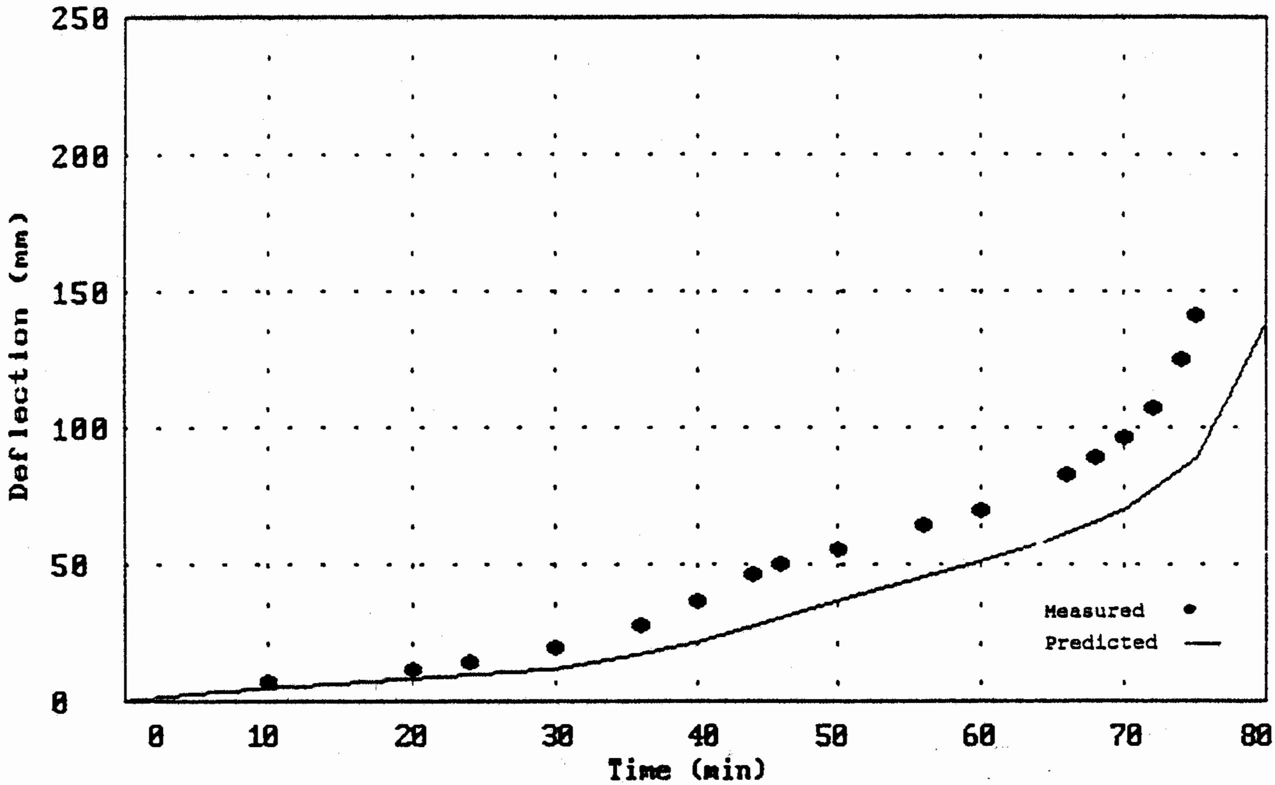


Figure 12. Measured and predicted temperatures in Test 3

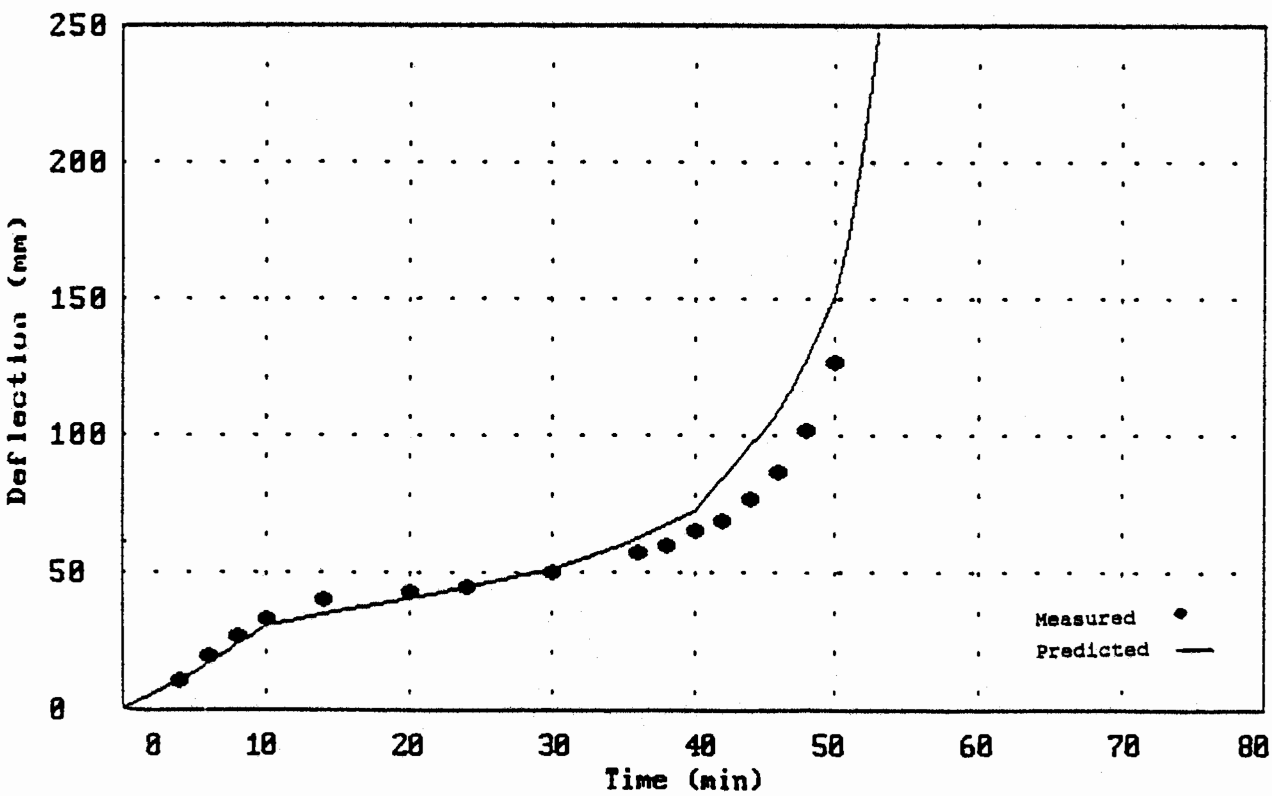


Figure 13. Measured and predicted temperatures in Test 4

7. ANALYSIS

7.1 Structural Behaviour of the Composite Beam

The behaviour of the composite beams has been modelled by SCI using their program BFIRE. This program uses a non-linear method of analysis which includes the shape of the stress-strain curves for steel at elevated temperature. It is purely a structural model; the temperature history of the beam has to be predicted using a thermal analysis program or entered as data, measured in a fire test.

The measured central deflection and the computed deflection are plotted for each test in Figures 10 to 13. Generally the comparison between measured and computed values is very good. This indicates that during the tests full composite action existed and little slip of the shear connectors occurred, as the program cannot model shear connector slip. In the third test, with cementitous spray, the computer model under-estimated the beam deflection. This could indicate that slippage between the steel beam and the concrete flange occurred. In test 3 the temperature of the bottom flange at failure was 524°C compared with an average of about 583°C recorded in the other tests. The only difference between test 3 and the other tests was the hotter top flange at failure of test 3. This was brought on by the thicker protection used in this test which permitted a greater temperature rise in the top flange because of the slower rate of heating of the bottom flange. The poorer performance in this test was probably due to the onset of failure of the shear connectors. However, even in test 3 the error in predicted fire resistance is only about 5 minutes. In general terms it can be said that the program, BFIRE is able to model the structural performance of composite beams in fire resistance tests.

Both the program and the fire tests indicate that the performance of the shear connectors was generally not critical. However the longest loaded test was for 74 minutes only. In test 2 the base temperature of a stud reached 594°C after 90 minutes (without load) compared with 466°C after 74 minutes of test 3. In a fire it is believed that the mode of failure of a shear connector would be shearing of the heated weld rather than failure of the concrete which is the governing mode at normal temperatures.

In assessing the limiting temperatures of composite beams the reduction in strength of shear connectors with temperature has been assumed. The assumption that the strength of shear connectors at elevated temperature is proportional to the reduction in strength of steel has been made. At 466°C (as measured in test 3) the studs are assumed to be at full strength (ignoring partial safety factors) and at 594°C (test 2) the stud strength falls to about 60% of its design strength.

Using the moment capacity method the limiting temperature for various load ratios has been computed. These are shown in Figure 14 for 60 minutes and 90 minutes fire resistance. In calculating the strength of the beams the top flange temperature has been assumed to be a multiple of the bottom flange temperature. The resulting temperature distributions corresponded closely to the measured values for 60 and 90 minutes.

In Figure 14 the limiting temperature is independent of the degree of shear connection. For 60 minutes it was found that full shear connection gave slightly lower limiting temperatures than lesser degrees of shear connection and for 90 minutes 40% shear connection gave the lowest limiting temperature. The values given therefore correspond to 100% shear connection for 60 minutes and 40% shear connection for 90 minutes. They are therefore slightly conservative.

7.2 Behaviour of Fire Protection Materials

SCI have analysed the performance of each of the three fire protection materials using the data recorded in the tests and other data provided by the protection manufacturers. This additional data has been supplied to SCI in confidence and therefore the details of the analysis carried out on each product is confidential.

In analysing the materials SCI used two published methods: the regression method used in the Yellow Book and the method given in BS 5950: Part 8. This latter method is based upon the method given in the draft of Eurocode 3 Part 10(7) and is based upon theoretical heat transfer. In addition to these published methods simple scaling techniques were also used.

The purpose of the analysis was to estimate:

a. The effect of the steel deck.
b. The effect of not filling voids.

The first of these is important in order to relate protection thicknesses for composite beams with steel decking to published data on protection thicknesses for non-composite beams.

The available data is generally based upon a limiting bottom flange temperature of 550°C for board and insulating sprays but 620°C for thin film intumescents. An analysis of a large number of practical composite beams has indicated that the maximum load

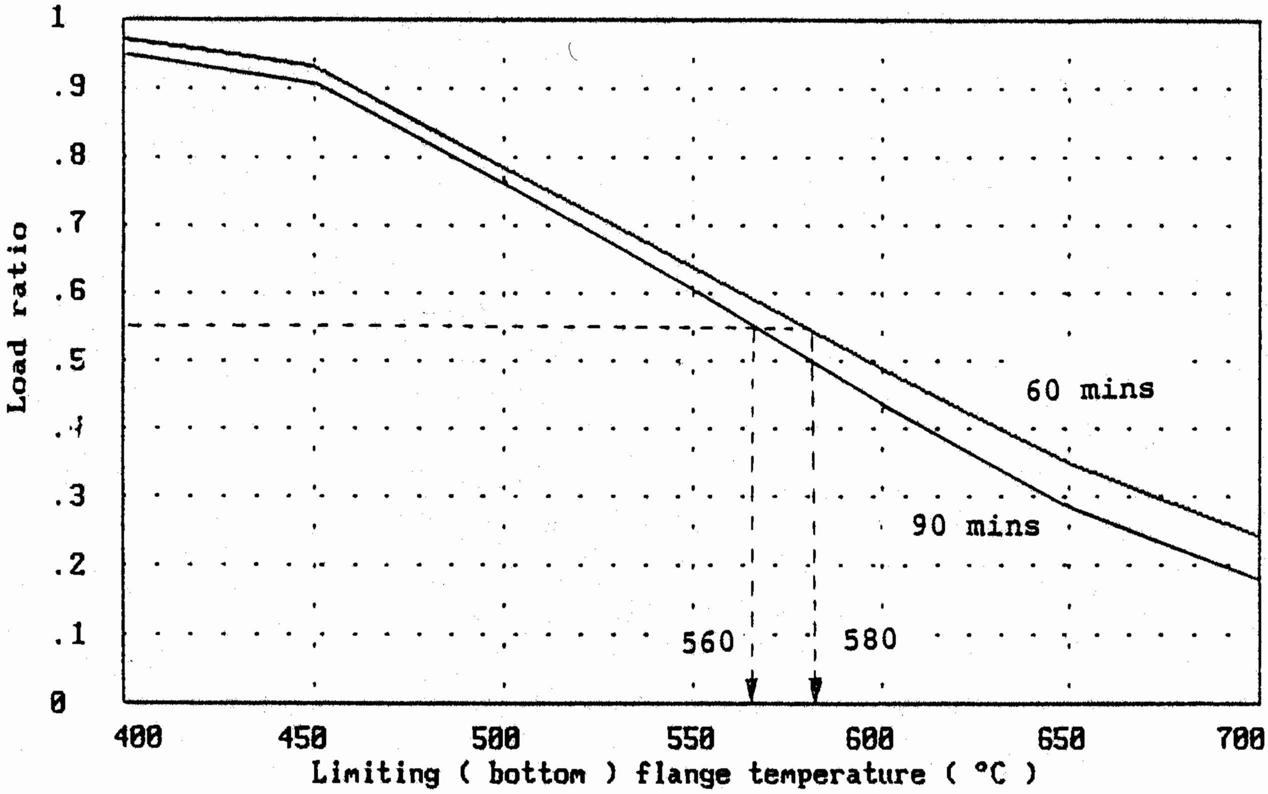


Figure 14. Load ratio vs limiting temperature for 60 and 90 minutes

ratio is 0.55. This corresponds to a limiting temperature of 580°C for 60 minutes fire resistance and 560 for 90 minutes. In ascertaining the effects of using steel decking temperatures with unfilled voids it is necessary to use these limiting temepratures and to estimate what modifications must be applied to published data based on assessments of 550°C or 620°C.

7.2.1 Board Protection

For the board protection system it is possible to obtain a direct measure of the increased rate of heating by comparison with the control test. The temperature of the lower flange increased by about 9% in the tests. This result was confirmed by an analysis carried out using additional test data provided by the material manufacturer. All the available data was analysed using the method given in BS 5950: Part 8 and reasonable correllation was found between the effective thermal conductivities calculated from various test results.

7.2.2 Cementitious Spray Protection

No direct comparison with other tests in this programme could be made so additional data applied by the manufacturer was used. It was found that compared to the beam with board protection the effect of unfilled voids was less pronounced. This is not unexpected because with the board system heat transfer can take place between the top flange and the lower flange via the internal voids. The increased rate of heating of the bottom flange was taken as 7% relative to the filled voids case. Again the method given in BS 5950: Part 8 was used to determine the thickness of protection.

7.2.3 Thin Film Intumescent Protection

The assessment of the performance of the intumescent coating was based upon the performance recorded in the test and on additional information supplied to SCI by the manufacturer. This information consisted of a recent fire test report and a detailed assessment of the product carried out by fire consultants.

In test 4 the bottom flange reached 580°C in 50 minutes. SCI estimate that for the beam size tested with a solid slab and no steel deck, 580°C would have been reached in about 59 minutes for the same coating thickness. This indicates that the bottom flange, which is the dominant structural component, receives about 18% more heat as a result of the exposed top flange.

7.3 Results of assessment of materials

7.3.1 Board and cemetitious spray protection

The measured and calculated differences between the systems was small and in view of the limited test data on which the assessment was based it was decided to treat the materials in a similar manner and not to produce separate guidance for board and spray protection of different types.

For 60 minutes fire resistance it was concluded that the thickness of fire protection assessed using 550°C would be adequate for a limiting temperature of 580°C for a composite beam with unfilled voids even for a slight increase in the rate of heating. For 90 minutes, using a limiting temperature of 560°C some increases in protection thickness are required. Additional protection should be based upon an increase in section factor of 10% or an increase in protection thickness by 5% compared to the published values for 550°C (see Recommendations).

7.3.2 Thin film intumescent coating

The basis for assessment of intumescent coatings is generally 620°C rather than 550°C which is used for passive insulating materials. The difference is due to the fact that steel beams fail in fire tests at about 620°C and columns at about 550°C (fully loaded to BS 449). Intumescent coatings are assessed separately for beams and columns but other materials are assessed more conservatively based on the single temperature of 550°C. In assessing the performance on composite beams with unfilled voids at limiting temperature of 580°C for 60 minutes and 560°C for 90 minutes the starting point is a thickness based upon 620°C and an indication from the test programme of an increased rate of heating with unfilled voids. It was concluded that for 60 minutes the increase in protection thickness should be taken as the lesser of 20% or the thickness appropriate to an increase in section factor by 30%. For 90 minutes these become 25% and 45% respectively. It is recognised that this assessment is based on a limited amount of data and is therefore conservative.

8. CONCLUSIONS

Four fire resistance tests have been carried out on composite beams. In one test the voids between the profiled steel deck and the top flange of the beam were filled and in the remaining tests the voids were left unfilled. The tests covered dry board, cementitious spray and thin film intumescent coating.

8.1 Structural Performance

Structurally, the test beams performed much as expected and in line with the SCI computer model. The computer prediction was very close to the test result with the exception of the third test. In this test failure occurred after 74 minutes compared with a predicted time of 85 minutes and with a bottom flange temperature 60°C lower than in the other tests. It was concluded that this was due to the onset of shear connector failure. Shear connector failure had not originally been expected and must therefore be taken into account when considering temperatures of the top flange greater than 700°C which occurs at fire resistances greater than 60 minutes.

Based on the measured temperature distributions and a realistic model of shear connector strength limiting temperatures for composite beams have been calculated at various load ratios for both 60 and 90 minutes fire resistance. At the maximum expected load ratio of 0.55 the limiting temperature was found to be 580°C for 60 minutes and 560°C for 90 minutes. For simplicity these values are quoted as independent of the degree of shear connection and are a lower bound to practical design cases. The degree of shear connection is known to influence the performance and can effect the limiting temperature by as much as 50°C. Further analysis of this effect is being carried out and the degree of shear connection will probably be included in a later design guide.

8.2 Thermal Performance

In each of the tests on beams with unfilled voids the beams experienced greater heating compared with the conventional test method utilising solid concrete slabs. The beam in the control test, with filled voids, did not appear to receive additional heating indicating that composite beams with conventionally filled voids require no additional protection.

The thickness of fire protection materials required for composite beams with unfilled voids has been analysed principally using the method given in BS5950: Part 8 (5) which is itself based upon the method given in EC3: Part 10 (6).

9. RECOMMENDATIONS

Recommendations for fire protecting composite beams with both filled and unfilled voids have been prepared and were issued separately on 2 July 1990. The recommendations are in two parts. The first part is for fire protection materials assessed in the ASFPCM/SCI Yellow Book at 550°C and the second part is for the thin film intumescents which are assessed at 620°C.

Since being issued on 2 July minor modifications have been made to clarify the position regarding the use of re-entrant profiled decking.

The research concentrated on upon trapezoidal decks and the re-entrant (closed dovetail) type of decks was not tested. Earlier tests indicated that the small voids formed with these decks have no significant effect on beam performance. No increases in fire protection are recommended for beams used with this type of deck. For completeness the recommendations include guidance for non-composite beams which support composite floors.

The use of unfilled voids is limited to a maximum of 90 minutes fire resistance. It is felt that beyond 90 minutes the performance of the shear connectors could not be safely guaranteed. Although not tested the use of shot fired shear connectors is not precluded. This type of connector has been shown to perform adequately in other fire tests.

9.1 Recommendations for Materials assessed at 550°C

a. Composite or non-composite beams with filled voids, or with re-entrant profiled decking having filled or unfilled voids; for all fire resistance periods.

   Recommendation: Use the ASFPCM/SCI guidance(2) to determine the fire protection thickness based on the section factor for three-sided heating.

b. Composite beams with unfilled voids and with open trapezoidal profiled decking.

   i. 60 minutes fire resistance:

      Recommendation: Use ASFPCM/SCI guidance, as above.

ii. 90 minutes fire resistance:

Recommendation: Use ASFPCM/SCI guidance as above, but either:

add 10% to the thickness of fire protection or,

add 15% to the section factor for three-sided heating when determining the thickness of fire protection (this is more appropriate for board-type materials).

The lower value given by the two methods may be used.

iii. 120 minutes or longer fire resistance:

Recommendation: Fill the deck voids above the flange.

c. Non-composite beams with open trapezoidal decking, for all fire resistance periods.

Recommendation: Fill the deck voids above the flange.

9.2 Recommendations for Materials assessed at 620°C

a. Composite or non-composite beams with filled voids or with re-entrant profiled decking having filled or unfilled voids; for all fire resistance periods.

Recommendation: Use the ASFPCM/SCI guidance (2) to determine the fire protection thickness based on the section factor for three-sided heating.

b. Composite beams with unfilled voids and with open trapezoidal profiled decking.

i. 60 minutes fire resistance:

Recommendation: Use ASFPCM/SCI guidance as above, but either:

add 20% to the thickness of fire protection, or

add 30% to the section factor for three-sided heating when determining the thickness of fire protection (this is more appropriate for board-type materials).

The lower value given by the two methods may be used.

ii. 90 minutes fire resistance:

Recommendation: Use ASFPCM/SCI guidance as above, but either:

add 30% to the thickness of fire protection, or

add 50% to the section factor for three-sided heating when determining the thickness of fire protection.

iii. 120 minutes or longer fire resistance:

Recommendation: Fill the deck voids above the flange.

c. Non-composite beams with open trapezoidal decking, for all fire resistance periods.

Recommendation: Fill the deck voids above the flange.

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APPENDIX A

Sponsors of the project

The project was sponsored by the following companies:

Alpha Engineering Services
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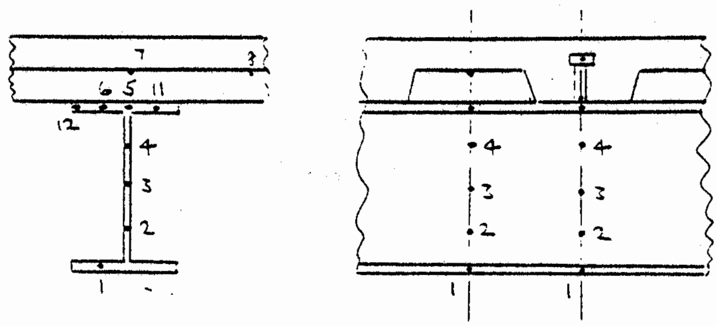
APPENDIX B - Temperatures and deflections recorded in Test 1

Note : Thermocouples are numbered as indicated in sketch.

Thermocouples 1 and 3 were also placed 1 metre from centre (1m c/c)



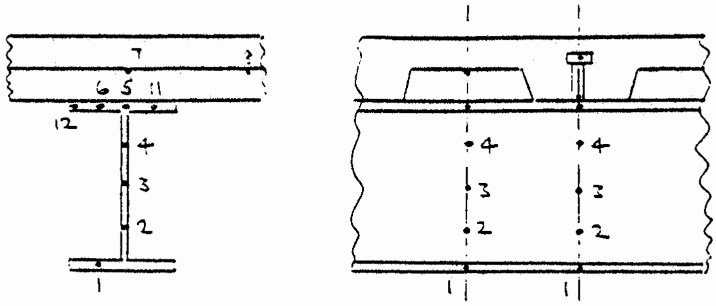
Composite Beam Test 1

Time	Beam temperature over void										Beam temperature over trough								1 m c/c		Shear stud		Central
	1	2	3	4	5	6	7	8	11	12	1	2	3	4	5	6	11	12	1	3	TOP	BOT	DFN
2	20	19	20	20	20	22	19	57	20	26	21	20	20	20	20	21	20	22	20	20	20	20	0
4	24	22	24	27	28	32	20	89	29	35	24	23	23	25	25	27	24	28	24	24	20	22	0
6	33	32	36	42	40	44	22	121	41	46	35	33	34	38	35	40	35	39	35	36	19	26	2
8	46	44	49	54	52	55	25	149	53	58	49	45	48	50	46	50	46	51	47	48	24	32	5
10	60	59	62	66	63	66	28	176	64	72	64	60	61	62	57	60	57	61	60	60	25	40	6
12	75	73	75	78	74	78	34	202	76	88	78	73	74	73	66	69	67	69	74	73	26	47	7
14	87	86	90	92	86	92	44	234	89	102	91	86	86	83	77	78	77	79	88	87	28	55	8
16	95	100	106	107	98	103	60	268	101	113	98	100	103	95	86	87	86	88	96	100	29	62	9
18	104	120	125	124	109	114	72	299	110	123	105	118	123	111	96	96	93	102	104	117	31	70	11
20	120	138	144	143	121	122	92	340	121	131	112	133	143	126	105	105	100	112	114	134	34	77	13
22	144	156	163	157	132	132	97	380	131	141	132	151	161	142	114	112	113	120	129	151	37	83	13
24	167	177	181	174	146	153	100	415	145	158	155	170	179	157	128	132	126	135	149	168	41	91	16
26	191	198	201	188	160	166	102	423	159	173	179	187	199	174	143	147	141	150	173	186	44	99	18
28	214	219	221	208	175	181	103	459	176	188	203	208	219	192	157	161	156	164	194	204	48	107	21
30	237	241	241	225	191	197	104	500	192	204	226	229	238	208	172	175	170	179	215	221	52	113	25
32	259	263	261	243	208	214	104	583	208	220	249	250	258	225	187	190	185	194	236	239	57	120	29
34	281	285	281	261	224	230	106	601	225	237	272	272	278	243	202	204	200	209	258	257	62	128	33
36	303	305	300	279	240	246	105	625	240	253	294	293	297	259	216	219	214	224	278	275	68	138	36
38	325	326	320	297	257	268	106	646	257	269	317	314	317	277	232	234	230	239	299	292	74	148	40
40	347	348	340	315	273	279	106	661	273	286	339	336	336	294	247	249	245	254	319	310	80	159	42
42	367	367	358	331	288	294	107	681	288	301	359	355	354	311	262	263	260	268	338	327	85	169	44
44	388	387	377	349	305	310	108	695	304	317	380	375	373	329	278	279	276	284	357	345	91	181	47
46	408	406	395	366	321	327	116	705	320	333	401	395	391	346	293	295	291	300	377	363	96	192	49
48	426	424	413	383	337	343	124	723	336	349	420	414	408	362	308	309	307	315	395	380	101	202	53
50	444	442	430	399	353	358	131	743	351	364	435	432	425	379	323	325	322	330	412	397	104	213	54
52	462	460	446	415	369	374	137	759	367	380	453	449	441	395	339	340	337	345	430	413	107	223	59
54	479	477	463	431	384	389	142	771	383	396	471	467	457	411	354	355	352	360	447.	429	109	234	61
56	496	493	479	447	400	405	145	791	399	411	487	483	473	426	369	369	367	375	463	446	110	245	62
58	512	509	494	462	416	420	158	797	414	426	504	500	489	442	384	384	382	390	479	462	112	256	69
60	528	524	509	477	430	434	160	812	428	440	520	515	503	457	398	398	396	404	495	477	115	266	75
62	543	539	523	491	445	448	167	827	442	455	535	530	518	471	412	413	410	418	510	492	118	277	85
64	558	553	537	506	458	463	173	836	457	469	540	544	531	485	426	426	424	432	524	507	122	287	95
66	570	567	551	519	472	477	177	846	470	482	556	559	545	499	439	440	438	445	538	521	127	297	109
68	584	580	564	532	486	490	186	858	484	496	575	573	558	513	453	454	452	459	551	535	132	307	136
70	597	593	576	545	500	502	195	868	497	508	602	588	573	527	467	469	466	472	565	550	138	317	-
75	627	622	605	575	531	534	211	889	526	540	626	619	605	561	500	502	499	505	597	583	152	343	-
80	657	652	635	606	564	567	226	908	563	573	654	650	637	593	533	535	532	538	629	615	167	371	-
85	682	677	660	633	593	596	235	914	591	601	678	674	662	620	562	563	561	567	656	642	182	397	-
90	706	699	683	658	625	623	252	925	619	628	700	698	687	645	589	590	587	594	582	668	196	424	-

APPENDIX C - Temperatures and deflections recorded in Test 2

Note : Thermocouples are numbered as indicated in sketch.

Thermocouples 1 and 3 were also placed 1 metre from centre (1m c/c)



Composite Beam Test 2

Time	Beam temperature over void 1	2	3	4	5	6	7	8	11	12
2	24	24	24	24	29	31	44	53	30	32
4	26	25	27	36	51	59	70	85	54	82
6	35	34	42	54	76	89	98	118	78	116
8	47	49	59	71	102	117	114	163	105	143
10	61	67	73	86	126	141	136	203	129	165
12	77	79	84	106	149	165	156	240	154	187
14	90	90	102	127	168	184	174	324	176	208
16	99	108	123	148	189	204	195	336	198	227
18	105	125	145	171	210	227	220	355	219	252
20	124	142	167	194	231	249	243	427	240	278
22	149	165	191	218	254	272	258	478	262	300
24	173	188	216	242	276	294	274	500	283	321
26	198	213	241	266	298	316	293	532	305	343
28	223	239	265	288	320	339	314	552	327	367
30	248	264	291	311	343	362	339	578	350	390
32	273	289	314	334	365	384	360	597	372	413
34	298	313	337	356	366	404	371	615	392	427
36	323	337	360	376	405	422	392	638	412	446
38	347	360	382	397	425	443	413	657	433	467
40	371	384	403	417	445	463	436	674	452	488
42	395	406	425	438	465	483	461	689	472	507
44	417	429	445	458	484	502	491	709	491	526
46	440	450	465	477	502	520	511	727	509	543
48	462	471	485	495	519	536	524	739	526	557
50	482	491	503	512	535	551	540	754	541	572
52	502	510	521	528	551	568	560	771	558	588
54	522	529	538	545	567	583	573	782	574	602
56	540	546	554	560	583	599	588	798	590	618
58	558	563	570	575	599	614	601	813	605	631
60	575	580	585	590	613	628	511	821	620	645
62	592	597	601	505	628	643	622	823	636	659
64	610	614	617	621	644	658	635	832	651	673
66	626	630	532	636	658	672	645	841	666	687
68	643	646	648	651	672	685	655	855	679	701
70	659	662	664	666	685	698	665	859	692	714
75	698	701	702	702	718	730	720	888	727	745
80	730	732	732	733	740	753	741	902	747	769
85	747	751	751	750	765	779	744	909	772	794
90	775	779	778	778	792	804	769	936	798	818

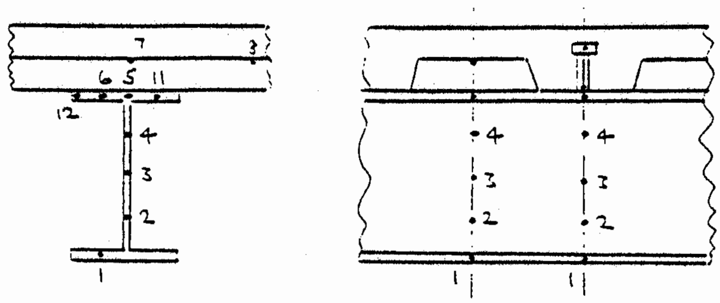
Time	Beam temperature over trough 1	2	3	4	5	6	11	12
2	24	24	24	24	24	24	24	25
4	26	26	28	31	34	40	35	50
6	34	35	42	48	50	56	52	66
8	46	50	58	64	64	71	66	81
10	60	67	72	76	77	85	77	95
12	75	79	84	91	92	103	92	111
14	89	95	101	111	111	120	115	128
16	98	110	123	134	131	140	135	147
18	101	128	145	157	152	161	156	171
20	119	147	168	179	171	182	175	193
22	146	170	192	203	193	202	195	216
24	171	194	216	226	213	222	215	235
26	196	219	241	249	234	243	235	256
28	221	245	265	282	254	273	255	278
30	246	270	291	294	275	284	275	301
32	271	295	314	317	295	305	295	323
34	296	319	337	339	315	325	314	337
36	320	343	359	360	334	342	335	355
38	344	366	381	379	352	360	354	373
40	368	388	402	400	371	379	372	394
42	392	411	424	420	390	398	391	412
44	415	433	444	440	408	416	409	428
46	437	454	464	459	426	434	428	446
48	459	474	483	477	444	451	445	462
50	479	494	501	495	461	468	462	479
52	499	513	519	511	477	484	479	495
54	519	531	537	529	494	500	496	511
56	537	548	553	544	509	516	512	525
58	555	565	569	560	525	331	527	538
60	573	582	585	575	539	545	542	552
62	591	598	600	591	554	560	558	565
64	610	616	617	607	570	575	573	580
66	628	633	633	623	584	590	588	594
68	645	650	648	638	599	605	603	610
70	662	667	665	654	614	621	618	622
75	700	704	702	691	651	657	655	660
80	729	733	729	720	682	687	686	690
85	759	761	755	744	707	713	712	715
90	782	784	778	765	727	734	759	737

Time	1 m c/c 1	3	Shear stud TOP	BOT	Central DFN
2	24	24	23	25	1
4	27	31	23	29	1
6	37	46	25	38	3
8	49	62	27	51	5
10	64	76	30	63	7
12	80	90	34	75	8
14	92	110	39	85	11
16	97	130	44	97	13
18	110	152	49	108	15
20	128	173	54	116	17
22	150	195	60	130	19
24	172	217	67	144	22
26	195	235	75	159	25
28	218	263	84	173	28
30	242	286	94	188	31
32	265	309	98	203	39
34	288	331	102	219	43
36	312	353	108	234	48
38	335	374	114	248	50
40	358	396	121	263	54
42	380	417	126	278	58
44	403	437	132	293	51
46	424	457	138	309	65
48	446	477	145	324	70
50	466	495	153	338	75
52	486	513	160	353	80
54	505	530	168	368	88
56	523	546	175	381	98
58	541	562	183	395	112
60	558	578	192	409	134
62	574	592	200	420	161
64	590	607	201	434	168
66	605	621	213	448	178
68	619	634	224	463	190
70	633	647	236	478	212
75	667	678	260	511	-
80	696	706	281	543	-
85	722	727	300	569	-
90	738	744	319	594	-

APPENDIX D - Temperatures and deflections recorded in Test 3

Note : Thermocouples are numbered as indicated in sketch.

Thermocouples 1 and 3 were also placed 1 metre from centre (1m c/c)



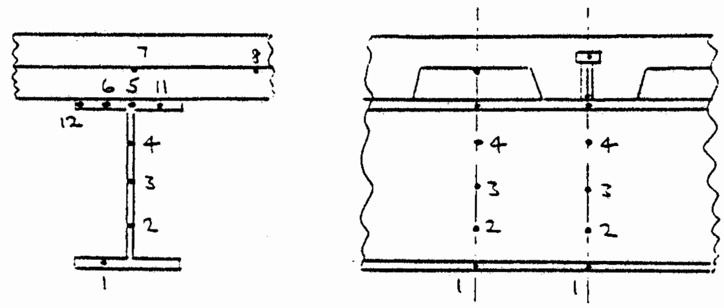
Composite Beam Test 3

Time	Beam temperature over void										Beam temperature over trough								1 m c/c		Shear stud		Void	Central
	1	2	3	4	5	6	7	8	11	12	1	2	3	4	5	6	11	12	1	3	TOP	BOT	VT	DFN
2	19	19	20	20	29	32	59	73	32	36	20	20	20	20	20	20	20	22	20	20	19	21	383	1
4	21	23	26	26	47	53	127	127	54	59	21	22	24	24	24	25	25	29	22	27	20	26	501	1
6	27	33	40	41	67	76	174	161	76	83	27	32	36	37	34	36	36	41	30	42	21	34	548	3
8	38	47	56	59	89	98	198	225	99	106	39	47	54	53	47	50	49	55	42	60	23	44	580	5
10	51	63	72	77	112	119	224	283	121	132	51	63	71	70	62	65	64	69	56	77	25	56	590	7
12	64	78	88	93	131	141	248	357	142	157	65	79	87	87	78	81	80	85	70	93	29	67	611	9
14	77	91	100	101	151	164	270	394	164	181	78	92	98	99	94	96	97	99	84	100	33	77	639	10
16	89	100	107	103	170	188	293	425	188	204	90	100	102	102	102	103	103	113	96	103	37	87	653	11
18	99	102	111	111	188	208	307	442	208	225	100	102	102	102	108	115	110	129	101	109	41	96	657	12
20	102	105	115	126	208	230	315	477	230	247	102	102	103	106	120	130	124	145	102	123	46	106	667	12
22	102	107	126	146	228	252	340	509	251	268	102	104	110	121	134	147	141	162	104	142	51	114	691	13
24	103	114	143	168	250	273	355	527	274	290	104	112	128	146	152	165	159	180	111	164	56	124	683	14
26	109	126	165	192	272	295	366	549	296	312	111	126	153	172	175	185	179	199	124	188	61	136	694	16
28	117	143	185	214	293	317	390	584	317	332	120	143	175	194	193	202	196	217	137	210	66	147	704	18
30	127	162	208	237	315	339	399	607	339	355	133	163	198	218	214	221	215	236	155	232	73	159	702	20
32	140	182	231	261	338	362	418	629	362	377	147	184	222	241	233	241	235	255	173	256	80	172	716	23
34	155	203	253	284	361	384	437	651	384	399	162	205	246	264	254	261	255	274	193	278	87	187	741	25
36	171	224	276	307	384	407	450	669	407	422	180	227	268	287	274	270	274	294	213	301	94	202	732	28
38	188	245	298	329	405	429	477	689	428	444	198	248	291	310	293	299	294	313	233	324	102	217	747	32
40	206	267	320	352	426	449	496	705	448	463	216	269	313	331	313	319	313	331	254	345	104	232	737	37
42	225	287	342	373	446	470	529	727	468	483	236	291	334	352	332	338	332	350	276	366	108	246	765	42
44	244	308	363	394	464	488	542	745	486	501	255	311	355	372	350	356	351	369	297	387	113	261	755	46
46	263	329	384	414	484	506	561	766	504	519	276	332	375	392	369	374	369	387	318	407	118	275	771	50
48	283	349	403	433	501	523	572	776	521	537	296	352	395	412	386	392	386	404	339	427	122	288	760	53
50	303	369	423	452	518	541	587	795	538	554	317	372	415	431	403	409	403	421	359	446	127	303	786	55
52	323	388	441	470	535	557	592	809	554	571	337	391	433	449	419	425	419	437	379	464	132	317	779	58
54	343	407	460	487	551	574	602	821	571	587	357	411	452	466	436	441	436	453	399	482	139	331	798	61
56	363	425	477	504	567	590	612	831	586	602	377	429	469	485	451	456	451	468	418	499	146	345	810	64
58	384	444	494	521	584	606	621	844	603	619	396	448	487	499	467	471	467	484	436	516	155	359	804	67
60	403	462	511	537	601	623	635	854	620	635	415	466	504	515	482	487	482	499	455	532	162	374	826	70
62	422	480	527	552	616	637	644	856	635	649	434	483	520	530	497	501	496	513	472	547	170	387	824	74
64	441	497	542	567	630	651	657	866	648	663	451	499	535	545	511	516	511	527	489	562	178	401	825	78
66	458	513	557	581	644	665	671	874	661	676	469	516	550	559	524	529	524	541	505	577	187	414	833	83
68	476	529	572	595	657	678	681	880	675	689	485	532	564	573	538	542	538	554	521	591	193	427	830	89
70	492	544	586	608	669	690	697	890	687	702	502	547	578	586	551	555	551	567	536	604	201	440	846	96
72	508	558	601	621	681	703	711	898	699	714	517	561	591	599	563	568	563	579	552	617	209	453	851	107
74	524	573	615	633	694	715	726	906	711	726	532	575	605	611	576	580	576	591	568	631	218	466	856	125
75	532	579	622	639	699	721	730	906	717	732	540	582	611	618	582	586	582	597	576	637	224	472	864	141
80	569	614	652	668	727	747	765	925	743	757	577	616	642	647	611	615	611	626	614	667	246	502	876	-
85	602	644	679	694	746	768	793	939	764	780	610	646	669	673	637	641	638	652	645	695	266	529	887	-
90	633	671	704	717	769	793	814	945	788	805	640	672	694	697	661	665	662	675	663	719	285	553	899	-

APPENDIX E - Temperatures and deflections recorded in Test 4

Note : Thermocouples are numbered as indicated in sketch.

Thermocouples 1 and 3 were also placed 1 metre from centre (1m c/c)



Composite Beam Test 4

Time	Beam temperature over void										Beam temperature over trough								1 m c/c		Shear stud		Void	Central
	1	2	3	4	5	6	7	8	11	12	1	2	3	4	5	6	11	12	1	3	TOP	BOT	VT	DFN
2	47	60	64	62	43	49	55	59	60	56	51	60	66	65	40	42	42	39	49	67	20	24	362	3
4	107	136	148	141	95	103	87	114	117	112	116	138	151	143	80	82	83	102	106	146	21	39	483	11
6	176	213	227	217	155	162	110	151	177	170	186	216	231	217	129	132	133	147	170	224	24	63	521	20
8	227	255	265	260	207	214	130	200	230	220	234	257	266	257	174	181	180	192	222	265	29	105	542	27
10	255	276	284	278	246	251	155	220	264	256	259	278	283	275	208	218	216	231	253	284	35	111	555	33
12	275	290	296	291	280	282	179	274	287	287	279	291	295	287	232	242	252	255	273	296	42	127	578	37
14	291	301	306	301	307	309	201	314	314	310	295	303	306	286	268	269	264	278	289	305	49	143	566	40
16	305	311	315	310	322	334	230	360	316	337	311	314	316	305	274	289	275	292	303	314	56	155	589	41
18	317	319	324	319	332	337	255	398	327	348	326	324	325	313	270	283	278	287	315	322	64	168	590	42
20	328	327	333	328	342	347	303	441	341	360	340	332	336	323	279	289	285	296	325	330	71	178	600	43
22	344	335	344	338	348	363	392	457	356	372	357	342	355	333	292	296	292	306	336	339	79	188	603	44
24	362	347	356	349	359	386	418	492	370	381	375	355	362	345	303	305	303	319	347	349	86	197	620	45
26	376	360	370	364	380	413	433	517	385	395	394	370	376	358	310	315	314	339	361	360	93	207	637	47
28	389	375	385	377	396	432	462	552	401	410	414	388	393	373	316	327	327	344	375	372	102	218	651	49
30	405	391	402	393	411	438	486	570	418	425	434	406	410	389	328	340	341	358	389	384	108	229	660	50
32	418	408	419	410	425	443	497	592	435	441	456	424	428	405	342	354	355	376	403	398	111	242	679	53
34	428	427	438	429	437	453	502	612	452	457	478	442	448	423	357	371	373	393	419	412	114	255	679	54
36	448	446	457	447	454	467	522	630	469	473	500	459	467	442	373	387	390	410	436	428	119	268	697	57
38	467	465	476	466	471	484	525	648	488	489	523	479	487	460	390	404	411	427	452	444	125	281	696	60
40	486	484	495	486	490	503	569	672	507	509	550	499	508	481	407	422	445	446	469	461	131	291	716	65
42	508	501	518	505	507	516	563	692	527	527	577	525	529	500	424	440	470	464	486	477	141	303	713	69
44	531	524	540	524	524	532	594	710	543	544	604	549	551	520	443	457	491	481	503	495	150	317	730	77
46	548	546	562	545	541	550	630	728	561	563	632	570	573	541	459	475	513	500	520	513	160	333	749	87
48	563	566	582	567	560	570	630	736	580	581	660	587	597	564	475	493	530	518	538	534	169	350	740	102
50	581	587	604	590	579	589	646	745	599	600	693	609	625	591	497	511	529	538	555	561	181	369	757	127
52	700	713	724	677	602	612	679	745	624	628	783	738	768	752	515	533	558	574	573	673	198	386	781	-
54	730	745	745	713	627	636	700	745	649	652	819	775	804	778	535	557	568	591	592	682	215	407	795	-
56	747	752	752	738	650	658	719	745	671	674	836	783	822	779	561	583	595	615	611	700	232	425	810	-
58	751	753	753	746	669	675	728	745	687	689	835	800	824	779	592	610	622	638	629	710	246	446	813	-
60	747	741	753	747	685	688	739	745	700	700	823	795	794	779	625	636	648	659	647	716	260	460	822	-

The Steel Construction Institute Silwood Park Ascot Berks SL5 7QN Telephone: (0990) 23345 Fax: (0990) 22944 Telex: 846843 CALCULATION SHEET	Job No. ONS 5100	Sheet 1 of 4	Rev.
	Job Title: Fire resistance of composite beams		
	Subject: Moment capacity (cold)		
	Client: JIP	Made by GMN	Date 26/2/90
		Checked by KFC	Date 18/4/90

Beam 305 x 102 x 33 UB

Grade 43 A ($p_y = 275$ N/mm²)

Slab 120mm x 2000 mm

Deck Ribdeck 60 (60 mm deep)

Concrete LW

Grade 30 (30 N/mm²)

a) Calculation based upon full shear connection

$$M_{pc} = R_s \left(\frac{D}{2} + D_s - \frac{R_s}{R_c} \left(\frac{D_s - D_p}{2} \right) \right)$$

M_{pc} = Plastic moment capacity

R_s = Tensile resistance of steel beam

D = Depth of steel beam

D_s = Depth of slab

R_c = Compressive resistance of slab

D_p = Depth of deck

[Calculation method given by "Design of composite slabs and beams with steel decking", SCI, 1989]

R_s : Area of beam = 41.8 cm²

$R_s = 41.8 \times 10^2 \times 275 \times 10^{-3}$

$= 1149.5$ kN

$D = 312.7$ mm

$D_s = 120$ mm

$D_p = 60$ mm

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CALCULATION SHEET

Job No. ONJ 5100		Sheet 2 of 4	Rev.
Job Title Fire resistance of composite beams			
Subject Moment capacity (cold)			
Client JIP	Made by GMN	Date 26/2/90	
	Checked by KFC	Date 18/4/90	

R_c : Area of concrete $= 2000 \times (120 - 60)$

$= 120000 \text{ mm}^2$

$R_c = 0.45 \times 30 \times 120000 \times 10^{-3}$

$= 1620 \text{ kN}$

$$M_{pc} = 1149.5 \times 10^{-3} \left(\frac{312.7}{2} + 120 - \frac{1149.5}{1620}\left(\frac{120-60}{2}\right)\right)$$

$M_{pc} = 293.2$ kNm

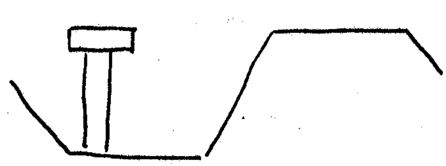
SCI have assumed that typically at the time of a fire a composite beam will have a load ratio of 0.55.

$M_{fire} = 0.55 \times 293.2$

$M_{fire} = 161.3$ kNm

b) Calculation based upon partial shear connection

Stud strength



Studs are all positioned to one side of trough ∴ use a 0.85 reduction factor

Characteristic stud strength $= 100$ kN

Design strength $= 100 \times 0.8 \times 0.85$

$= 68$ kN

No. of studs in half span $= 7$

∴ $R_q = 7 \times 68 = 476$ kN

The Steel Construction Institute Silwood Park Ascot Berks SL5 7QN Telephone: (0990) 23345 Fax: (0990) 22944 Telex: 846843 **CALCULATION SHEET**	Job No. ONS 5100	Sheet 3 of 4	Rev.
	Job Title Fire resistance of composite beams		
	Subject Moment capacity (cold)		
	Client JIP	Made by GMN	Date 17/6/90
		Checked by	Date

% shear connection $= \dfrac{R_q}{R_s}$

$= \dfrac{476}{1149.5} \times 100$

$= 41.4\%$

M_s = Plastic moment capacity of steel beam

$= 479.9 \times 275 \times 10^{-3}$

$= 131.97$ kNm

R_w = Resistance of web

$= 1149.5 - 2 \times 102.4 \times 10.8 \times 275 \times 10^{-3}$

$= 541.2$ kN

$R_v = d\,t\,p_y$

$= 275.8 \times 6.6 \times 275 \times 10^{-3}$

$= 500.6$ kN

$$M_{pc} = M_s + R_q\left(\frac{D}{2} + D_s - \frac{R_q}{R_c}\frac{(D_s - D_p)}{2}\right) - \frac{R_q^2}{R_v}\cdot\frac{d}{4}$$

$$= 132 + \frac{476}{10^3}\left(\frac{312.7}{2} + 120 - \frac{476}{1620}\frac{(120-60)}{2}\right) - \frac{476^2}{500.6}\times\frac{275.8}{4\times10^3}$$

$= 228.1$ kNm

c) The above calculations have been repeated using actual material properties

$p_y = 295$ N/mm^2

$f_{cu} = 55$ N/mm^2

Full shear $M_{pc} = 320$ kNm

Partial shear $M_{pc} = 244$ kNm

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CALCULATION SHEET

Job No. ONS 5100	Sheet 4 of 4	Rev.	
Job Title: Fire resistance of composite beams			
Subject: Load Ratio			
Client: JIP	Made by G.M.N.	Date 17/6/90	
	Checked by	Date	

$$\text{Load Ratio} = \frac{\text{Moment in fire}}{\text{Moment capacity at } 20^\circ C}$$

$M_{fire} = 161.3$ kNm

a) Based on nominal properties

Full shear $\quad LR = \dfrac{161.3}{293.2} = 0.55$

Partial shear $\quad LR = \dfrac{161.3}{228.1} = 0.71$

b) Based on actual properties

Full shear $\quad LR = \dfrac{161.3}{320} = 0.50$

Partial shear $\quad LR = \dfrac{161.3}{244} = 0.66$