Chapter 11
Fire Resistance of Protected Slim Floors

Abstract The insulating effectiveness of intumescent coatings for fire protection is evaluated, using computer models and software, based on fire test data. The procedure include: (i) examination of testing set-up and data, and correction of temperature data obtained from small furnace tests on unloaded beams; (ii) evaluation of beam temperature distribution as a function of protective coating type and thickness; (iii) calculations of moment resistance and load ratio for any given coating thickness and the determination of minimum coating thickness required for different periods of fire resistance up to 120 min; (iv) extension of calculation results for different beam sizes; (v) examination of the effect of service holes; (vi) assessment for different types of coatings on asymmetric beams by comparison with test data on Slimflor beams. The coating thickness sufficient for all types of slim floor construction is obtained.

In slim floor construction, the supporting floor beam is contained within the depth of the floor deck. This provides a solid flat slab appearance similar to reinforced concrete construction. The fabricated Slimflor beam, developed by British Steel (now Tata Steel) and The Steel Construction Institute (SCI), is based on a universal column section, with a single horizontal plate welded to its bottom flange (Fig. 10.1). The floor can be constructed of pre-cast concrete units or long span composite slabs with deep profiled steel decks. The purpose of this chapter is to evaluate the thickness required for specified fire resistance, for two commonly used intumescent coatings.

The asymmetric beam (ASB), developed by British Steel (now Tata Steel) and The Steel Construction Institute (SCI), does not require welding of an additional plate, as the Slimflor beam does, and achieves optimum properties for design. The floor is constructed of long span composite slabs with deep profiled steel decks (Fig. 11.1). Because the asymmetric beams are almost totally contained within the floor slab, they have inherently good performance in fire and in most cases can achieve 60 min fire resistance without applied protection. However, for more than 60 min fire resistance, protection must be applied to the bottom flange. Such fire protection can effectively be provided in the form of intumescent coating, which will add a negligible amount to the depth of the section. The required thickness, however, would be much smaller than that needed for normal universal

W. Sha, *Steels*, DOI: 10.1007/978-1-4471-4872-2_11,

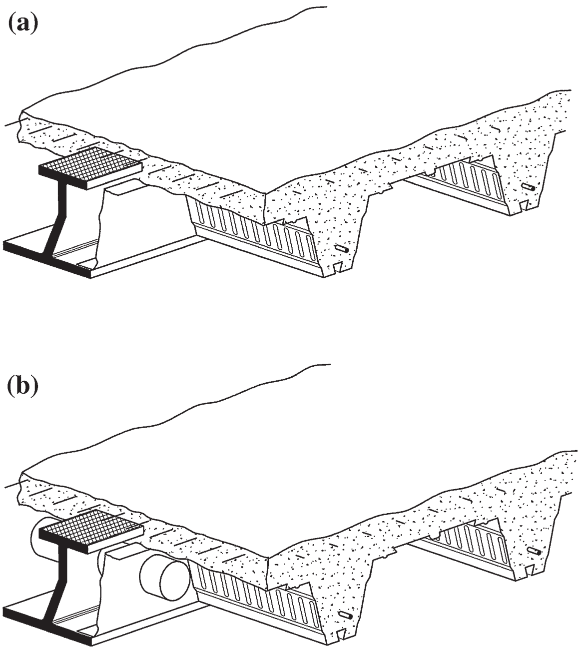

Fig. 11.1 Diagrams of typical slim floors using asymmetric beams. **a** Without service holes; **b** with service holes. From Sha (2001b)

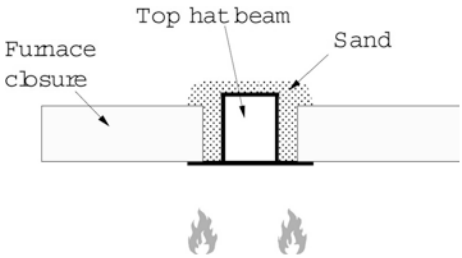

Fig. 11.2 Schematic of SINTEF tests. From Sha (2001a)

beams. The purpose of Sect. 11.7 is to evaluate the coating thickness required for specified fire resistance, for a commonly used intumescent coating.

11.1 Fire Tests

A series of fire test were carried out at Norwegian Fire Research Laboratory (SINTEF) to examine the intumescent paint system S607 for fire protection of the Scandinavia design of Top-Hat or HQ slim floor beam (Fig. 11.2). Two beam sizes were used, with lower flange thickness of 10 and 30 mm, respectively. By comparison, it was found that the temperatures of the former are closer to those of the UK Slimflor system, and results from this size are therefore used here. The relevant data are summarised in Table 11.1. Temperatures in brackets are the corresponding

Table 11.1 Temperature (°C) at bottom flange and lower part of web of Top-Hat slim floor beam at 60, 90 and 120 min from a test conducted in SINTEF programme

Coating thickness (g/m^2)	Time (min)	Bottom flange	Lower web
300	60	718 (721)	488 (529)
	90	811 (823)	595 (617)
	120	868 (915)	663 (688)
900	60	532	331
	90	673	459
	120	747	545

temperatures measured in the Nullifire furnace. Coating thickness in this chapter is always quoted by the wet weight per square metre of surface area (g/m^2). These will be used to evaluate the effect of coating thickness of S607 on beam temperatures.

Six fire tests were carried out at Nullifire Ltd. on unloaded Slimflor beams protected using S607 and S605 intumescent coatings. The furnace temperature was made to follow the standard fire curve. In all tests UC 203 × 203 × 60 beams were used and the bottom plates were 15 mm thick and approximately 200 mm wider than the flange of the UC section. The first test carried out was on an unprotected slim floor beam. This was to enable comparison to be made with Warrington Fire Research Centre (WFRC) test data. In the tests, only the bottom plate, where the intumescent protective coatings were applied, was directly exposed to fire, and the UC section welded to the plate was buried in sand (Fig. 10.12a). This made the experiments considerably easier to conduct as casting and drying of concrete were avoided, although the beam temperature development would be somewhat different compared with situations where the beam is covered by concrete. The correction of temperatures due to this factor will be discussed in detail in Sect. 11.2.1. The positions of thermocouples in each section are shown in Fig. 10.12b.

In addition to the tests on Slimflor beams one test was conducted on section of beam previously tested at SINTEF. The purpose of this test was to show that the Nullifire furnace had similar heating characteristics to the SINTEF furnace. The results of this test are included in Table 11.1, in brackets. The data from this test has been treated as informative only because the assessment in this chapter is for Slimflor beams rather than the HQ beam. However, the temperatures compared well with the Nullifire temperature being slightly higher than the SINTEF values. This is an indication that the Nullifire furnace is more severe than the SINTEF furnace.

Although the detailed temperature–time profiles for all 12 thermocouples on each test run are available, data directly useful for the modelling are average temperatures of plate, bottom flange and the lower part of the web (referred to as lower web throughout this chapter) at 60, 90 and 120 min. These are summarised in Table 11.2. The top flange temperature is always below 400 °C and therefore the steel is at full strength.

Fire tests at Warrington Fire Research Centre (WFRC) were carried out in a large furnace on loaded bare beams. Among a number of tests made, two are particularly relevant to the modelling here, in terms of their value in temperature

Table 11.2 Temperatures (°C) at various locations of Slimflor beams at 60, 90 and 120 min from tests conducted at Nullifire Ltd

Coating type	Thickness (g/m^2)	Time (min)	Plate	Bottom flange	Lower web
Unprotected	0	60	836	701	480
		90	953	858	608
		116	1,004	942	688
		120	1,016	949	698
S607	300	60	687	588	414
		90	802	708	522
		120	903	806	598
S605	600	60	559	418	336
		90	714	557	446
		120	818	655	529
S605	1,200	60	483	406	279
		90	605	532	377
		120	718	641	465
S605	2,000	60	388	282	216
		90	498	377	291
		120	608	477	368

Table 11.3 Temperatures (°C) at various locations of Slimflor beams at 60, 90 and 120 min from tests conducted at WFRC

Test	Beam in	Time (min)	Plate	Bottom flange	Lower web
UC 203 × 203 × 60	Sand	60	838	693	496
		90	934	848	652
		110	990	897	697
		116 (test ended)	1,023	946	761
UC 254 × 254 × 73	Concrete	60	803	603	339
		90	932	806	506
		110 (test ended)	994	878	578

corrections. The first was carried out on a beam identical to those tested at Nullifire Ltd., with the space above the plate covered by sand. The second test was on a slightly larger beam, a UC 254 × 254 × 73 Slimflor, covered by concrete, to simulate a situation closer to real practice. The test results shown in Table 11.3 were derived from tests and therefore form a basis for the corrections of the data obtained from Nullifire tests.

11.2 Data Treatment and Numerical Modelling

The approach adopted is to first show that for protected sections the performance in the Nullifire furnace is close to that at SINTEF. Second, the performance in the Nullifire furnace is compared with that measured at WFRC.

The comparison with SINTEF was only used in a qualitative sense as the tests at SINTEF were on a Top-Hat beam which, although being a slim floor beam, is not the same as the Slimflor beam studied in this chapter.

11.2.1 Temperature Corrections of Nullifire Data

The moment resistance of the Slimflor beams in fire conditions can be calculated knowing the beam temperature distribution data. Here, three different kinds of temperature corrections are made before such calculations. These are:

(a) correction between tests at Nullifire and WFRC;
(b) correction due to testing in sand;
(c) correction from pre-cast condition to decking.

Tests with bare steel Slimflor beams at a same size (203 × 203 × 60) were conducted in both Nullifire and WFRC, their results included in Tables 11.2 and 11.3. The differences in measured temperatures are taken as correction factors for temperature readings obtained in Nullifire tests (Table 11.4). There are at least two reasons for this correction to be necessary. First, the WFRC tests were carried out on longer and loaded beams, and therefore represent a more realistic situation. Second, the effectiveness of the modelling package was validated against experimental results from WFRC.

The derived corrections for up to 90 min are comparatively small indicating that the Nullifire furnace is similar to the WFRC furnace. For greater than 90 min, the only significant difference is in the lower web.

All Nullifire tests were carried out with the space around the I-beam above the bottom plate filled with sand. The difference in thermal behaviour between sand and concrete would influence the beam temperature, and this is taken into account by using a temperature correction factor. This factor is obtained by comparing the temperatures between the two tests carried out at WFRC (Table 11.3). Although the tests were conducted on beams of slightly different size, the thickness of the bottom flange of UC 203 × 203 × 60 and UC 254 × 254 × 73 is identical (14.2 mm). In such a case the beam temperature distribution would be very similar and the beam size effect is negligible. The correction factors are given in Table 11.5.

In practice, a Slimflor may be used with pre-cast concrete or constructed using a composite slab with deep decking. While a pre-cast concrete floor completely shelters the steel beam except the bottom plate from fire, a decking system leaves

Table 11.4 Temperature correction factors due to different testing furnace used (°C, + indicating that the WFRC measured temperatures are higher)

Time (min)	Plate	Bottom flange	Lower web
60	+2	–8	+16
90	–19	–10	+44
116[a]	+19	+4	+73

[a]Time closest to 120 min where data are available and used as correction for temperatures at 120 min

part of the UC covered with only a relatively thin layer of concrete. Therefore, the latter represents a more severe condition regarding structural response to fire. However, all Nullifire tests were conducted in a pattern essentially analogous to a pre-cast system. As the eventual design tables for the required coating thickness will be for the most severe fire situation, a temperature correction is made to derive temperature distributions of beams in a decking system (Table 11.6). This correction is based on work by SCI and is related to the observed differences between Slimflor beams constructed using pre-cast flooring and deep decking.

Total correction factors are obtained by summing up the correction factors for each cause shown in Tables 11.4, 11.5 and 11.6. This is listed in Table 11.7. All further modelling and analyses are made with data corrected using this table.

11.2.2 Temperature Distribution as a Function of Coating Thickness

Temperatures at plate, bottom flange and lower web as functions of coating thickness are required for predicting the effectiveness of any given thickness. For S607 coating, temperature reduction factors due to increased coating thickness are derived from both Nullifire and SINTEF results. For S605 coating, this is achieved

Table 11.5 Temperature correction factors due to testing in sand (°C, – indicating that the measured temperatures with sand were higher)

Time (min)	Plate	Bottom flange	Lower web
60	–35	–90	–137
90	–2	–42	–146
110[a]	+4	–19	–119

[a]Time closest to 120 min where data are available and used as correction for temperatures at 120 min

Table 11.6 Temperature correction factors due to decking (°C, + indicating that temperatures with decking are higher than temperatures with pre-cast units)

Position	Plate	Bottom flange	Lower web
Pre-cast	788	578	447
Decking	829	628	467
Correction	+41	+50	+20

Table 11.7 Total temperature correction factors (°C, + indicating that the measured temperatures in the Nullifire furnace should be increased)

Time (min)	Plate	Bottom flange	Lower web
60	+8	–48	–101
90	+20	–2	–82
120	+64	+35	–26

Table 11.8 Temperature decrease (°C) per 100 g/m^2 increase of S607 coating thickness

Location	Plate		Bottom flange		Lower web	
Thickness range (g/m^2)	0-300	>300	0-300	>300	0-300	>300
60	49.7	31.0	37.7	31.0	22.0	26.2
90	50.3	23.0	50.0	23.0	28.7	22.7
120	37.7	20.2	47.7	20.2	33.3	19.7

Table 11.9 Temperature decrease (°C) per 100 g/m^2 increase of S605 coating thickness

Location	Plate			Bottom flange			Lower web		
Thickness range (g/m^2)	0–600	600–1,200	>1,200	0–600	600–1,200	>1,200	0–600	600–1,200	>1,200
60	46.2	12.7	–	47.2	2.0	–	24.0	9.5	–
90	39.8	18.2	–	50.2	4.2	–	27.0	11.5	–
120	33.0	16.7	13.8	49.0	2.3	20.5	28.2	7.1	12.1

with the Nullifire test data for the bare beam, and those coated with different thickness. The method, to calculate the temperature decrease per 100 g/m² increase of coating, involves basically the interpolation of the test data, of the temperature with thinner coating and the temperature with thicker coating.

For S607, coating thickness dependence of section temperature is estimated using the SINTEF and Nullifire data in Tables 11.1 and 11.2, respectively, for different thickness ranges. This is obtained in the form of temperature decrease for every increase of 100 g/m^2 of coating thickness, as summarised in Table 11.8. As a Top-Hat beam does not have a plate welded to its bottom flange, the temperature characteristics for its bottom flange are used for both the plate and bottom flange in a Slimflor beam.

For S605, coating thickness dependence of section temperature is estimated using the Nullifire data in Table 11.2, for different thickness ranges. This is obtained in the form of temperature decrease for every increase of 100 g/m^2 of coating thickness, as summarised in Table 11.9.

11.3 Design Tables for 60, 90 and 120 min Fire Resistance

The reduced moment resistance in fire conditions is calculated using plastic theory, as permitted. The basic methodology adopted is to obtain load ratios for the given temperature distribution (i.e. temperatures in plate, bottom flange and lower web) which is in turn determined by the type of coating (S607 or S605) and its thickness. The load ratio is defined as the ratio of load applied at the fire limit state and load capacity under normal 'cold' conditions.

The calculations are conducted assuming that the beam is designed at room temperature as a composite beam using a deep steel deck with 85 mm concrete cover

Table 11.10 Load ratio as a function of coating thickness with the minimum safe thickness indicated in bold

Fire resistance (min)	S607		S605	
	Thickness (g/m^2)	Load ratio	Thickness (g/m^2)	Load ratio
60	0	0.49	0	0.49
	100	0.55	100	0.55
	200	0.64	**200**	0.66
90	500	0.53	500	0.58
	600	0.57	**600**	0.68
	700	0.62	700	0.71
120	1,300	0.56	1,300	0.53
	1,400	0.60	1,400	0.57
	1,500	0.64	**1,500**	0.60

above the top of the beam. The shear connection percentage is taken as 40 % in 'cold', increased to up to 100 % in fire. All calculations are carried out for the beam size used in Nullifire fire tests, i.e. 203 × 203 × 60 with 15 mm thick bottom plate, with no service holes. The fire performance of Slimflor beams designed as composite beams is not as good as beams designed as non-composite so, these conditions represent the most severe fire situation that could be encountered in normal construction, and therefore the results would in fact give additional safety factors for many practical cases. Except where tests were made for the given coating condition, fitted temperature distribution functions given in Tables 11.8 and 11.9 are used.

The detailed results are given in Table 11.10. The minimum thickness corresponds to a load ratio of 0.6, which is adequate for almost all applications.

11.4 Larger Beams

As stated earlier, the design table (Table 11.10) is based on calculations for a relatively small beam size, 203 × 203 × 60. The question remains as to the behaviour of larger beams in a fire condition. To clarify this, further modelling work using TFIRE, a computer program developed at The Steel Construction Institute, is conducted to calculate the temperature of beams at different sizes. The details of physical models used in this program and its good accuracy are described elsewhere (Chap. 10).

In TFIRE, the protection effect of normal fire protection board can be modelled with good confidence. The approach used here starts from finding a suitable board thickness that will give a similar temperature distribution after 120 min in a standard fire, for a 203 × 203 × 60 Slimflor beam. Then, temperature distributions for larger beams protected with a same board thickness are calculated (Table 11.11), together with calculated safe load ratio for each temperature distribution.

It is clear from the table that the larger beams would have lower temperatures at a given time. This is reasonable as the larger volume of the section will certainly

Table 11.11 Temperature distribution of different beams with the same thickness of fire protection board at 120 min and the corresponding safe load ratio

Beam	Average temperature (°C)		Safe load ratio
	Plate	Bottom flange	
203 × 203 × 60	769	620	0.57
254 × 254 × 73	767	627	0.60
254 × 254 × 107	739	588	0.68
305 × 305 × 283	663	492	0.87

need more heat to heat up, and the heat within the section will dissipate more quickly, too. Therefore, the small beam of 203 × 203 × 60 represents a more severe fire proposition, and the calculation given in Table 11.10 should be safe when applied to larger beams.

11.5 Effect of Service Holes and Stickability

For a Slimflor beam with service holes in its web, its temperature during a fire will be higher. The extent of this temperature increase was measured experimentally in a fire test carried out on a bare Slimflor beam at Warrington Fire Research Centre. The test was carried out on a 254 × 254 × 73 UC beam with a 460 × 15 plate. The temperature increase as a result of increased exposure to fire due to service holes is 72 and 139 °C for plate and bottom flange, respectively, at 60 min, and 64 and 142 °C for plate and bottom flange, respectively, at 90 min. The configuration of the test is equivalent to a practical situation where the holes are left empty, and therefore usually most vulnerable to the heat, in a fire.

The basic approach in evaluating the effect of service holes is as follows:

(1) Obtain temperature values at plate and bottom flange for a given coating thickness using test data given in earlier sections and Tables 11.8 and 11.9;
(2) Increase the temperatures to a level that will be experienced for beams with service holes using data earlier in this section and as discussed below; this approach is regarded as conservative;
(3) Calculate the moment resistance from such a temperature distribution taking into account of the reduction in web area.

In stage 2, the temperature at the remaining lower part of the web is taken as that at the bottom flange minus 35 °C, as proved to be reasonable from earlier calculations. Also, as there are no data as regard to the temperature increase at 120 min due to holes in the web, data for 90 min are used. The part of the UC section above the hole is assumed to be always below 400 °C. Although the part of the web immediately above the hole is likely to reach a higher temperature, it would contribute very little to the overall strength in any case.

In stage 3, the UC beam size used in calculation is 203 × 203 × 60, as for the above calculations for the beam without service holes. The relatively small

Table 11.12 Load ratio as a function of coating thickness for Slimflor with service holes with the minimum safe thickness indicated in bold

Fire resistance (min)	S607		S605	
	Thickness (g/m^2)	Load ratio	Thickness (g/m^2)	Load ratio
60	400	0.59	300	0.52
	500	0.67	**400**	0.65
90	1,000	0.55	800	0.59
	1,100	0.61	**900**	0.62
120	1,800	0.56	2,000	0.58
	1,900	0.61	**2,100**	0.63

size difference between the test beam and the beam adopted for calculation would only influence the final load ratio results to a minimal extent. A hole diameter of 160 mm is used, with the remaining web height below the hole being 15.8 mm.

With this method, the load ratio resistance, i.e. the ratio between moment resistance at the fire limit state and that under normal 'cold' conditions (both with web holes), is given in Table 11.12. The minimum thickness corresponds to a load ratio of 0.6.

Comparing this table with Table 11.10, it can be seen that increases of between 200 and 600 g/m² are required to fire protect Slimflor for same periods of times, with the actual amount generally in proportion to the thickness for a normal beam. The calculations here, like previous calculations for normal beams, represent a conservative estimate. In design guide for Slimflor construction, the hole diameter is limited to 0.6 of the depth of the UC section. Due to the parameter setups in the program, the service hole diameter of 160 mm is above 0.6 of the depth of the 203 × 203 × 60 beam. Therefore, the calculation results should cover all sizes of service holes used in practice.

For S605, the value of 2,100 g/m^2 corresponding to 120 min fire resistance represents an extrapolation as the maximum thickness tested was 2,000 g/m^2. The thickness of 2,000 g/m^2 would allow a load ratio of 0.58 to be achieved on a 203 section. This thickness would be adequate for virtually all circumstances, as service holes are normally only installed in beams more than 250 mm deep.

The assessment carried out above is based on the insulating properties of the coatings. An assessment of the stickability of the products by Fire Safety Engineering Consultants Ltd., UK has concluded that the 'stickability' of the coatings should be adequate for the assessed fire resistances and protection thickness.

11.6 Summary for Slim Floors Protected Using Intumescent Coatings

The effectiveness of two Nullifire intumescent coatings, S607 and S605, for the fire protection of Slimflor beams is evaluated using a combination of experimental fire tests and numerical data treatments, modelling and calculation.

A number of fire tests, carried out at three locations, i.e. Nullifire, Warrington Fire Research Centre, and Norwegian Fire Research Laboratory (SINTEF), are examined and their data compared. Based on corrected temperature data, and the interpolated as well as extrapolated coating thickness dependence of beam temperature distribution, load ratio that can be afforded by protection of any given thickness of coating can be obtained.

We give the required coating thickness adequate for all types of construction using Slimflor. For a fire resistance of 60 min, a nominal thickness of 200 g/m^2 of either S607 or S605 will be enough. For fire resistance of 90 min, the required thickness is 700 and 600 g/m^2 for S607 and S605, respectively. For 120 min fire resistance, a thickness of 1,400 g/m^2 of S607 or 1,500 g/m^2 of S605 is needed. An increase in coating thickness of between 200 and 600 g/m^2, depending on coating type and fire resistance period, is required for beams with service holes in the web.

An assessment of the stickability of the products by Fire Safety Engineering Consultants Ltd., UK has concluded that the 'stickability' of the coatings should be adequate for the assessed fire resistance and protection thickness.

11.7 Asymmetric Slim Floor Beams

11.7.1 Tests

Several fire tests were carried out at Warrington Fire Research Centre. An unloaded asymmetric beam whose bottom face was protected using the S605 intumescent coating (Fig. 10.13a) was included in the tests. In the test, only the bottom flange was directly exposed to fire, and the rest of the section was surrounded by concrete. Half of the beam, the left-hand side, was coated with a relatively thin layer of S605 coating, at a density of 500 g/m^2. The coating for the right-hand half was relatively thick, 1,500 g/m^2. The number below the section symbol indicates the number of thermocouples at each section (A–H).

The positions of thermocouples in each section are shown in Fig. 10.13b. In sections with only five thermocouples, they are at positions 1, 3, 5, 8 and 11.

In the following, concerning the protected beam, temperatures at sections B and G were used, as these sections:

(a) are away from the mid-span position where the coating thickness changes;
(b) have full sets of 12 thermocouples;
(c) should have higher temperatures due to heat passing through the end diaphragm.

Although the detailed temperature–time profiles for all thermocouples are available, data directly useful are average bottom flange temperatures and temperatures at various positions in the lower part of the web at 90 and 120 min (Table 11.13). Note that each bottom flange temperature is the average of five

Table 11.13 Measured temperatures (°C) at various locations of the asymmetric beam at 90 and 120 min in the fire test

Coating thickness (g/m^2)	Time (min)	Bottom flange	TC5	TC6	TC7	TC8
500	90	630	558	528	464	384
	120	717	643	612	547	465
1,500	120	587	527	506	445	378

thermocouple readings (positions 1–5). The upper part of the web (positions 9 and 10) and the top flange temperatures (positions 11 and 12) are always below 400 °C and therefore the steel is at full strength.

11.7.2 Numerical Modelling and Load Ratio Calculation

The reduced moment resistance in fire conditions is calculated using plastic theory, as permitted. The steel section is split into eight elements as shown in Fig. 11.3. The width and height of each of the eight elements are given in Table 11.14. The reduction of strength of each element is obtained from factors (based on 2 % strain), depending on the temperature of the element, which was obtained from measurements during the test. The concrete is split into four elements. The basic methodology adopted is to obtain load ratios for the given temperature distribution which in turn is determined by the coating thickness.

The temperatures of elements 2 and 4 are interpolated from the temperature readings from adjacent thermocouples. Taking into account of the distances between the centroid positions and adjacent thermocouples does this, and the formulae are given in Table 11.14. Small differences exist for the flange widths but these should have only marginal effect on load ratio calculations.

Based on the method described above, the load ratio, which is the ratio between the load applied at the fire limiting state and the load resistance under

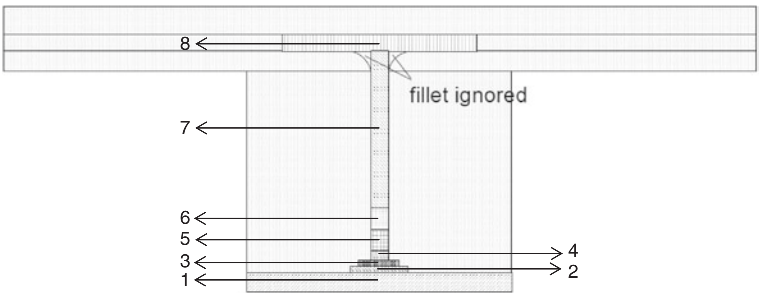

Fig. 11.3 Cross-section split into elements for moment resistance calculation. From Sha (2001b)

Table 11.14 Steel element width and depth (mm) used in the model (from bottom to top in Fig. 11.3)

Element	Width	Depth	Temperature corresponding to test
1	300	18	(TC1 + TC2 + TC3 + TC4 + TC5)/5
2	43.7	6.4	0.64·TC6 + 0.36·TC5
3	30.8	6.4	TC6
4	18	7.2	0.68·TC6 + 0.32·TC7
5	18	20	TC7
6	18	20	TC8
7	18	184	≤400
8	190	18	≤400

normal 'cold' conditions, is obtained. Calculated load ratios for the asymmetric beam protected with 500 g/m² S605 coating are 0.71 and 0.53, at 90 and 120 min, respectively. In the calculation, bond stress limits (bond strength) of 0.9 and 0.6 N/mm² are used for hot and 'cold' conditions, respectively, in accordance with experimental testing result.

The temperatures in the half of the beam protected with 1,500 g/m² coating are considerably lower than those with 500 g/m² coating (*compare* data in Table 11.13: 1,500 g/m² at 120 min and 500 g/m² at 90 min). Therefore, the load ratio that will be afforded in the former condition should be well above 0.71. The load ratio for an unprotected asymmetric beam is 0.50.

11.7.3 *Coating Thickness Required for 120 min Fire Resistance*

From Sect. 11.7.2, a coating thickness of 500 g/m² can only protect for load ratios up to 0.53 for 120 min fire resistance, while a thickness of 1,500 g/m² overprotects. In the following, the appropriate coating thickness for achieving a load ratio of 0.6, which, for ASB, is adequate for all applications, is given.

Coating thickness dependence of section temperatures at 120 min is estimated using test data in Table 11.13, for the thickness range between 500 and 1,500 g/m². This is in the form of temperature decrease for every increase of 100 g/m^2 of coating thickness. The temperature decrease per 100 g/m^2 increase of S605 coating thickness at 120 min is 13.0, 10.9, 10.6, 10.5, 10.2, and 8.7, for elements 1-6 from bottom of beam, respectively.

Using temperature distributions interpolated based on these, the load ratios achievable are 0.57, 0.60 and 0.63, for coating thickness of 700, 800 and 900 g/m², respectively, for 120 min fire resistance. The minimum safe thickness corresponds to a load ratio of 0.6.

11.7.4 Effect of Service Holes

In an asymmetric beam with service holes in its web (Fig. 11.1b), the temperature will be higher during fire. The extent of this temperature increase was measured experimentally on an bare asymmetric beam at Warrington Fire Research Centre, in a fire test carried out at the same time as the one described in Sect. 11.7.1. The temperature differences between hole and hole-free regions are summarised in Table 11.15. The configuration of the test is equivalent to a practical situation where the holes are left empty, and therefore usually most vulnerable to the heat, in a fire.

The basic approach in evaluating the effect of service holes is as follows:

(1) Obtain temperature values at various elements (Fig. 11.4) in bottom flange and lower web for a given coating thickness using test data given in earlier sections and Sect. 11.7.3;
(2) Increase the temperatures to a level that will be experienced for beams with service holes using data in Table 11.15 and as discussed below; this approach is regarded as conservative;
(3) Calculate the moment resistance from such a temperature distribution taking into account of the reduction in web area (Fig. 11.4).

In stage 2, temperature interpolations using same formulae as used before are used for temperature increase factors. Also, as there are no data as regard to the temperature increase at 120 min due to holes in the web, data for 90 min are used. The part of the web above the hole and the top flange are assumed to be always below 400 °C. Although the part of the web immediately above the hole is likely

Table 11.15 Temperature increase (°C) at various locations as a result of increased exposure to fire due to service holes

Time (min)	Bottom flange	TC5	TC6	TC7
60	40	59	81	137
90	38	74	100	169

Fig. 11.4 Steel cross section with hole. From Sha (2001b)

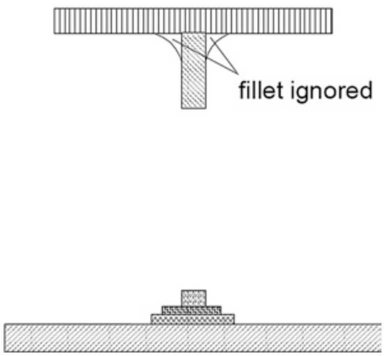

Table 11.16 Load ratio as a function of coating thickness for asymmetric beam with service holes with the minimum safe thickness indicated in bold

Fire resistance (min)	Thickness (g/m^2)	Load ratio
60	**500**	0.82
90	1,000	0.59
	1,100	0.64
120	1,500	0.48
	1,800	0.58
	1,900	0.62

to reach a higher temperature, it would contribute very little to the overall strength in any case.

In stage 3, the beam size used in calculation is the same as for the above calculations for the beam without service holes. A hole-diameter of 160 mm is used, with the remaining web height below the hole being 20 mm.

With this method, the load ratio resistance, i.e. the ratio between moment resistance at the fire limit state and that under normal 'cold' conditions (both with web holes), is given in Table 11.16. The minimum thickness corresponds to a load ratio of 0.6.

Comparing this table with the calculations for the beam without holes (Sect. 11.7.3), it can be seen that increases of 600 or 1,100 g/m² are required to fire protect for 90 and 120 min, respectively. For 60 min fire resistance, the assumed minimum thickness practically applicable, 500 g/m², is enough. The calculations here, like previous calculations for normal beams, represent a conservative estimate as a hole diameter of 160 mm is the maximum permissible in the design guide, while the beam used in the calculations is small in the range of asymmetric beams.

Although there are no fire test data of ASB slim floor protected with S607, comparative data do exist for Slimflor beams protected with S605 and S607. These have been extensively evaluated in previous sections in this chapter, revealing only marginal difference in the behaviour of the two types of coatings. Here, the required thickness of S607 to fire protect ASB is obtained by using the results for S605 discussed in previous sections and taking into account of the differences between the two coatings as calculated from Slimflor test data. S607 coating thickness required for all types of ASB construction is 500 and 700 g/m² for up to 90 min and 120 min fire resistance, respectively, in the case of no service hole. With service hole, this will be 500, 1,300, and 1,700 g/m², for 60, 90, and 120 min fire resistance, respectively.

11.7.5 Summary

The effectiveness of the Nullifire intumescent coating S605 for the fire protection of asymmetric slim floor beams is evaluated using a combination of experimental fire testing and numerical modelling and calculation. A fire test carried out at Warrington Fire Research Centre is examined. Based on the temperature data, and the extracted information on coating thickness dependence of beam temperature distribution, load ratio that can be afforded by protection of any given thickness of coating can be obtained.

For fire resistance of up to 90 min, a nominal thickness of 500 g/m^2 will be enough. For 120 min fire resistance, a thickness of 800 g/m^2 is needed. For beams with service holes in the web, coating thickness of 500, 1,100 and 1,900 is required for 60, 90 and 120 min, respectively.

It is important to note that the assessment here is based on the apparent insulating properties of the coatings. It has not considered the 'stickability' of the coatings, or has made any judgement as to whether the assessed thickness is practical.

References

Sha W (2001a) Fire resistance of slim floors protected using intumescent coatings. In: Topping BHV (ed) Proceedings of the eighth international conference on civil and structural engineering computing. Civil-Comp Press, Stirlingshire, Paper 65. doi:10.4203/ccp.73.65

Sha W (2001b) Fire resistance of protected asymmetric slim floor beams. In: Topping BHV (ed) Proceedings of the eighth international conference on civil and structural engineering computing. Civil-Comp Press, Stirlingshire, Paper 67. doi:10.4203/ccp.73.67