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The Fire Resistance of Shelf Angle Floor Beams to BS 5950: Part 8

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FOREWORD

This Technical report was prepared by Mr G M Newman of The Steel Construction Institute based on the requirements of BS 5950, *Structural use of steelwork in building*, Part 8: *Code of practice for fire resistant design*. The research into the behaviour of shelf angle floor beams was funded by British Steel - Sections, Plates and Commercial Steels and the fire tests were carried out by British Steel Technical, Swinden Laboratories.

SCI Technical Reports

Technical Reports are intended for the rapid dissemination of research results as and when they become available. They provide an opportunity for interested members to comment and offer constructive criticisms, so that a refined design guide can be produced eventually, after taking into consideration the comments received.

Please forward your comments to Mr G M Newman, The Steel Construction Institute, Silwood Park, Ascot, Berkshire, SL5 7QN.

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SUMMARY

Tests have shown that shelf angle floor beams supporting precast concrete floors have good inherent fire resistance. The shielded upper part of the section remains cool as do the upper parts of the angles that support the precast slabs. Together, these cooler and hence stronger parts of the section are capable of resisting applied moments in fire. Appendix C of BS 5950: Part 8 gives a method of evaluating the fire resistance of shelf angle floor beams. The method is based on the moment capacity approach in which the plastic moment capacity of the section, including the angles, is calculated at elevated temperatures.

Included in this report are design tables which give the highest position at which the angles can be placed on the beam to achieve a certain moment capacity in fire. This position therefore relates to the portion of the beam that is exposed. Tables are given for a range of Universal Beam sizes for grade 430 and 510 steels and for 30 and 60 minutes fire resistance. A design example is also given.

NOTATION

B_e	Width of exposed bottom flange
D_e	Overall exposed depth of beam
G	Temperature gradient
H	Minimum protected depth of section for a given load and fire resistance
k_R	Strength reduction factor
M_f	Moment on beam at the fire limit state
M_{ft}	Transverse bending moment on angle
M_{cf}	Moment capacity of shelf angle floor beam
p_y	Design strength of steel
R	End reaction
t	Thickness of element
Z	Elastic section modulus
θ_x	Temperature at location x
θ_R	Temperature at angle root
S_x	Plastic section modulus about the major axis of the section

1. INTRODUCTION

Shelf angle floor beams supporting precast concrete units are a practical structural option to reduce construction depths. The precast units, instead of resting on the top flange of the beam, are supported by angles bolted or welded to the web of the beam. In this way construction depths can be reduced as the depth of the precast unit is contained within the beam depth. An additional benefit of shelf angle floor construction is improved performance in fire where the leg of the angle is embedded in the slab and the upper part of the beam is partially shielded by the concrete floor. This fact alone will cause a reduction in the amount of fire protection required because the exposed perimeter of the steel is reduced.

Research carried out by British Steel and SCI[1] has shown that in many instances the fire protection can be totally eliminated by taking account of the strength retention of the cooler parts in comparison to the exposed parts of the section. Fire resistances of 30 and 60 minutes can be readily achieved depending on the applied load. It is appreciated that the analysis of shelf angle floor beams in fire can be relatively complicated because of the considerable variation of temperature through the cross-section. Therefore, emphasis has been placed on the preparation of simplified design tables for shelf angle floor beams of different depths carrying different loads.

The guidance in this document is based on the calculation method described in BS 5950: Part 8 *Code of Practice for fire resistant design*[2] and in a *Handbook to BS 5950: Part 8* published by the SCI[3].

2. GENERAL DESIGN REQUIREMENTS

A general arrangement of a shelf angle floor beam for fire conditions is shown in Figure 1. The precast units may be standard proprietary units but must have reduced or solid ends in order that they provide the necessary insulation to the steel. This point is further discussed in Section 4. For adequate fire resistance it is essential that the gap between the web and concrete is filled with grout or concrete to ensure that an effective heat sink is created around the section.

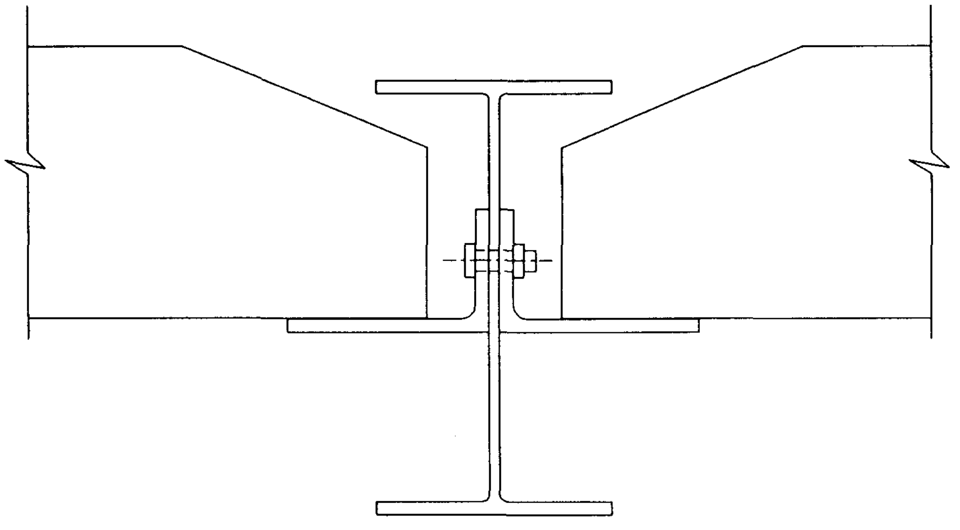

Figure 1 *General arrangement for shelf angle floor*

The design of an unprotected shelf angle floor beam is virtually the same as the traditional design of a shelf angle floor beam. The only significant difference is the inversion of the angles so that the short legs point upwards and are thus shielded from direct exposure to fire. The angles are not normally designed to act structurally with the beam at normal design temperatures although it is essential that they act with the beam in fire conditions. The angles may be bolted or welded to the beam.

In fire, the precast units protect the upper part of the section resulting in only moderate rises in temperature whilst the exposed lower part heats up rapidly and typically can exceed 900°C after 60 minutes. The effective section resisting bending comprises the top flange, the upper web and the vertical legs of the angles. The lower part of the section is only capable of contributing a small amount to overall bending capacity.

3. METHOD OF DESIGN

BS 5950: Part 8 states that the strength of a beam in fire may be considered adequate if the moment capacity at elevated temperature is greater than the applied moment in fire. The Code describes a method for calculating the moment capacity which is based on rectangular stress blocks comprising the reduced strength of the various elements of the beam in fire. The method is used to determine the reduced plastic moment capacity of the section in fire as a function of the temperatures given in the Code. By comparison with the performance in actual fire resistance tests it can be demonstrated that the 'moment capacity' method is conservative.

SCI and other research organisations have developed alternative mathematical models which are less conservative than the moment capacity method but still conservative when compared to tests. These calculations can only be practically carried out using a computer and are not strictly in accordance with the Code. The design tables in this publication are based on the method given in Appendix C of BS 5950: Part 8 and are conservative because of the many beneficial factors that are ignored.

At elevated temperatures, the strength retention of steel to be used in design is based on 1.5% strain at all points in the cross-section (Table 1 below, also Table 1 of BS 5950: Part 8). However, in fire, strains greater than 5%, are often experienced in bending members. This leads to a significant increase in strength of the highly strained elements due to strain hardening. The 1.5% strain value is therefore conservative. It may be noted that Eurocode 3: Part 1.2[4] will use a limiting strain of 2% giving slightly higher strengths than in BS 5950: Part 8.

In addition to a moment capacity calculation, BS 5950: Part 8 recommends that the transverse bending of the angles as well as the connection of the angles to the beam are checked. Both these points are illustrated in the design example in Section 7 of this publication.

Table 1 *Strength reduction factors for steel to BS 4360 grades 430 and 510*

STRAIN %	TEMPERATURE OF STEEL °C									
	300	400	450	500	550	600	650	700	750	800
0.5	0.854	0.798	0.721	0.622	0.492	0.378	0.269	0.186	0.127	0.071
1.5	1.0	0.956	0.898	0.756	0.612	0.460	0.326	0.223	0.152	0.108
2.0	1.0	0.971	0.934	0.776	0.627	0.474	0.337	0.232	0.158	0.115

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BS 5950: Part 8 recommends a tabular method for obtaining the temperature distribution across the section. This method is based on test measurements and is a close fit to the measured temperatures. The general form of the distribution is shown in Figure 2.

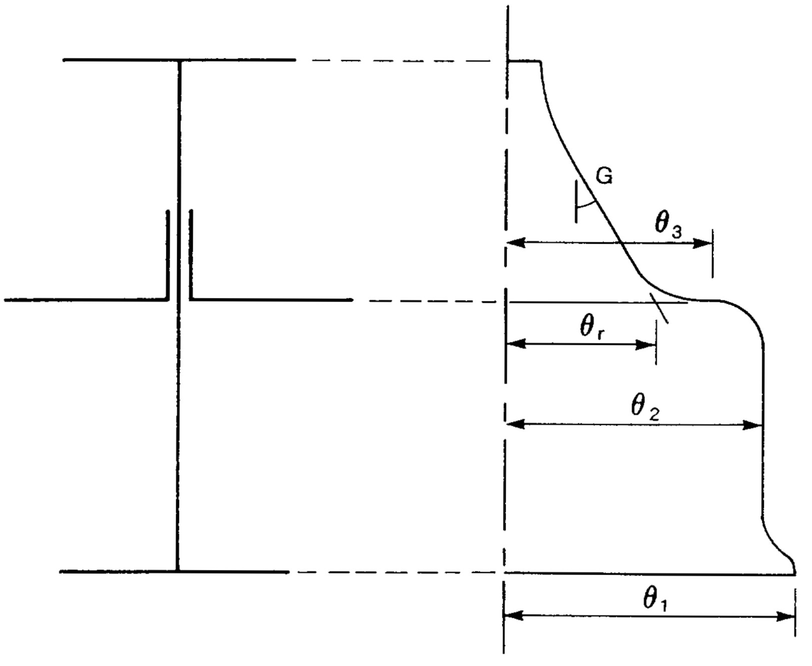

Figure 2 *Temperature distribution in a shelf angle floor beam*

4. RECOMMENDATIONS OF BS 5950: PART 8

BS 5950: Part 8 Appendix C recommends the following design conditions:

a) Precast concrete slabs should be made of normal weight concrete and should not have any deliberately designed voids in the end 75 mm of their length.

b) The void between the precast slab and the beam should be filled with grout.

c) Precast floor slabs should have at least 75 mm of bearing on the angles.

d) The steel angles should be of grade 510 steel, not less than 125 × 75 × 12 mm, fixed with the longer legs supporting the concrete slabs, and the vertical leg upwards as shown in Figure 1.

e) The connections at either end of the beam should either be contained wholly within the depth of the floor slab or else fire protected to the same degree as the supporting member.

f) The moments due to the loads transmitted via the slab at the fire limit state, should not exceed the transverse moment capacity of the angles at the required period of fire resistance (M_{cf}) given by:

$$M_{cf} = 1.2\, p_y\, Z\, k_R$$

where

p_y = the design strength of steel;

Z = elastic modulus of angle leg = $t^2/6$ per unit length;

t = thickness of angle leg;

k_R = the strength reduction factor from Table 1 (also Table 1 in BS 5950: Part 8) for 1.5% strain, for the temperature of the angle at the fire limit state.

g) The angles may be welded or bolted to the beam. In addition to resisting the applied vertical loads at the fire limit state, the connection of the angles to the beam should be capable of transmitting the longitudinal shear force necessary to develop the required axial forces in the angles at the point of maximum moment. Any weld below the angle should be ignored. In these calculations the strengths of welds and bolts should be taken as 80% of the relevant design strength at elevated temperature, derived using the appropriate strength reduction factor for steel from Table 1 using a 0.5% strain limit.

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The most important of the above points relates to the precast slab. The recommendation that there should be no deliberately designed voids in the end 75 mm is very onerous and may not be easy to achieve economically. The purpose of the recommendation is to ensure that the slab acts as an adequate heat sink to prevent excessive heating of the steel beam. Manufacturers can press the ends of each precast unit whilst the concrete is still 'green'. This will have the effect of closing the circular holes which are normally cast into the units. While this may not strictly meet the 75 mm recommendation of a) above, it will achieve the intent of providing an effective heat sink, in conjunction with the grout infill between the precast unit and the steel beam.

Tests carried out since the publication of BS 5950: Part 8 have shown that grout is much more able to absorb heat than the dry sand which was used to fill the area between the beam and the precast units in the original test programme. Alternatively the holes may be filled, prior to erection, with grout but this may prove expensive.

A typical pressed end detail for a precast unit is shown in Figure 1.

5. PRACTICAL DETAILS

Shelf angle floors may present a problem during construction due to difficulties in locating the precast units. In order to place the units the angles need to be relatively wide, but to reduce the transverse bending of the angle the units should be as long as possible. The units should also be located with approximately equal gaps at both ends. It is strongly recommended that the recommendations of the manufacturers or suppliers are followed or that any design is carried out by an engineer experienced in using shelf angle floor construction.

The design information presented here is based on the assumption that the beams are adequately restrained during construction.

The design tables given do not include any steel beams of depths less than 300 mm. It is considered that beams below this depth cannot practically be used as shelf angle beams.

6. DESIGN TABLES

The moment capacity of a shelf angle floor beam increases as the proportion of the section that is protected by the concrete floor units increases, i.e. it increases as the angles are placed lower down the section. For a range of universal beam sizes and load ratios the highest position that the shelf angle may be placed below the top of the beam has been computed and is given in Tables 2, 3, 4 and 5. The position, H, of the angle is measured from the top of the steel beam to the top surface of the horizontal leg of the angle (Figure 3).

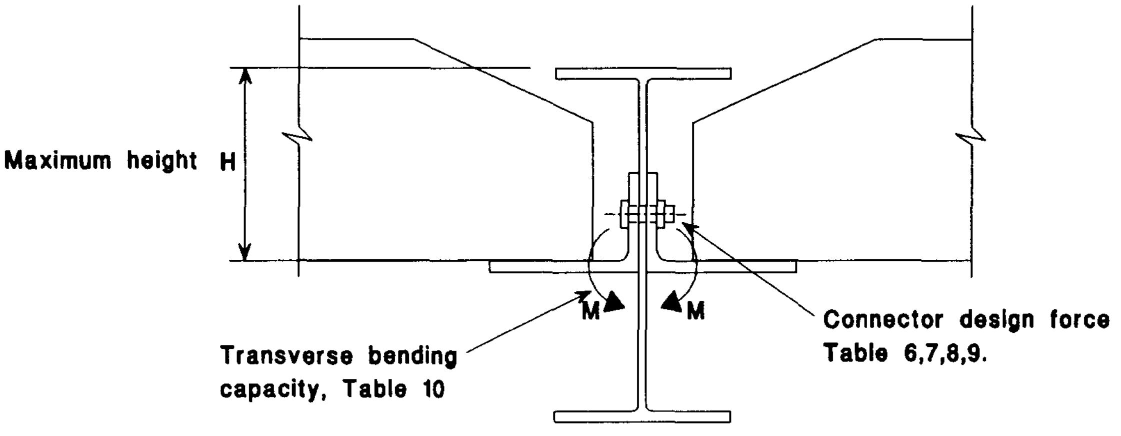


Figure 3 *Design factors*

The load ratio is defined as:

$$\frac{\text{Moment capacity at fire limit state}}{\text{Moment capacity of beam at normal temperature}}$$

Typical load ratios for well designed beams are in the range 0.45 to 0.55. For convenience the moment capacity at normal temperature is also given. This has been calculated as $p_y\ S_x$.

The angle has been assumed in every case to be 125 × 75 × 12 mm, grade 510 steel. Some beams will require a larger angle. The effect of increasing the size of the angle has been investigated and found to have little effect on the moment capacity of the beam section.

The connection between the angles and the beam should be designed to transmit the horizontal load given in Tables 6 to 9, as appropriate. (Also, see Section 4).

The angles must be checked for transverse bending. The bending capacity of 12 mm thick angles is given in Table 10. (Also, see Section 4).

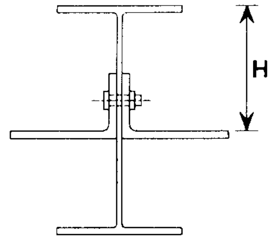
Tables 11 and 12 define the temperature distribution in the section.

The use of all the design tables is illustrated in the design example.

Table 2 *Design table for shelf angle floor beams in fire*

Fire Resistance	**30 mins**

Beam Grade	**Fe430**
Angle Grade	**Fe510**



Section size	M_p (kNm)	*H* (mm), the position of the angle below top of beam for load ratio of:						
		0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	93	82	82	82	91	108	123	137
× 28	112	84	84	84	101	118	133	148
× 33	132	86	86	90	108	125	141	156
305 × 127 × 37	149	86	86	94	112	124	140	155
× 42	168	87	87	98	116	128	144	160
× 48	194	89	89	104	122	133	150	166
305 × 165 × 40	172	85	85	97	115	128	145	161
× 46	199	87	87	100	118	131	148	165
× 54	232	89	89	104	124	136	154	171
356 × 127 × 33	148	84	92	113	132	149	163	179
× 39	180	86	97	119	139	157	170	187
356 × 171 × 45	213	86	101	123	144	162	176	194
× 51	246	88	103	126	147	167	180	199
× 57	277	90	103	127	149	169	183	202
× 67	333	96	110	134	157	174	192	211
406 × 140 × 39	198	98	123	145	166	185	200	217
× 46	244	99	126	149	171	189	207	225
406 × 178 × 54	288	110	135	152	174	196	211	231
× 60	328	109	135	150	175	197	213	234
× 67	370	111	138	154	178	201	217	238
× 74	414	115	143	159	184	207	223	244
457 × 152 × 52	301	124	153	178	201	221	239	259
× 60	353	121	151	179	204	225	243	264
× 67	396	124	155	183	208	229	247	269
× 74	430	128	159	187	212	232	252	274
× 82	477	125	158	187	214	235	255	278
457 × 191 × 67	405	130	159	176	202	227	245	266
× 74	456	130	161	178	205	230	248	271
× 82	504	134	165	182	210	235	252	276
× 89	534	135	166	184	212	238	255	279
× 98	591	129	162	180	210	237	256	281
533 × 210 × 82	565	161	195	215	244	272	298	317
× 92	651	163	197	219	249	278	303	324
× 101	694	164	199	222	251	281	306	328
× 109	748	161	198	223	251	282	308	330
× 122	849	154	194	227	250	282	312	334
610 × 229 × 101	793	189	228	261	285	317	347	368
× 113	871	191	231	265	289	322	354	376
× 125	974	181	224	263	285	321	355	379
× 140	1099	179	224	265	287	326	363	387
610 × 305 × 149	1212	163	211	255	280	323	363	366
× 179	1463	157	175	230	280	303	352	372
× 238	1976	106	106	106	166	214	288	315

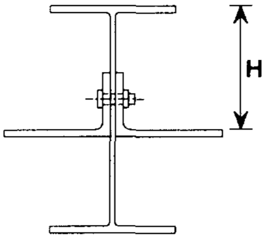
Notes for Tables 2 and 3:

- M_p is the moment capacity (cold) of the Universal Beam which forms the shelf angle beam.
- The maximum load ratio that may be sustained in fire for the design conditions is tabulated. Hence the moment capacity in fire is M_p × Load ratio. *(continued)*

Table 3 *Design table for shelf angle floor beams in fire*

Fire Resistance	30 mins

Beam Grade	Fe510
Angle Grade	Fe510



Section size	M_p (kNm)	*H* (mm), the position of the angle below top of beam for load ratio of:						
		0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	120	82	82	93	110	125	139	152
× 28	145	84	84	100	117	133	148	159
× 33	170	86	86	105	123	139	155	166
305 × 127 × 37	192	86	90	108	121	137	153	168
× 42	217	87	92	112	123	140	157	170
× 48	251	89	96	116	127	145	162	174
305 × 165 × 40	222	85	91	110	123	141	157	172
× 46	257	87	92	112	125	143	160	175
× 54	300	89	95	116	129	148	166	178
356 × 127 × 33	192	86	107	127	146	160	176	192
× 39	232	89	112	132	152	165	183	200
356 × 171 × 45	275	96	114	136	156	170	188	205
× 51	318	98	115	138	159	173	192	210
× 57	358	101	115	139	161	175	195	214
× 67	430	104	121	145	168	182	203	223
406 × 140 × 39	256	112	136	158	178	193	212	229
× 46	315	113	138	162	183	199	218	237
406 × 178 × 54	372	122	139	163	186	207	223	242
× 60	424	121	140	162	186	209	224	245
× 67	478	122	141	165	190	213	228	250
× 74	534	126	143	170	195	215	234	256
457 × 152 × 52	388	137	164	190	213	229	251	271
× 60	456	133	163	190	215	231	254	275
× 67	512	136	166	194	219	235	259	280
× 74	560	139	170	198	224	240	264	286
× 82	621	136	169	198	225	242	267	290
457 × 191 × 67	522	142	169	187	214	238	255	278
× 74	588	142	171	189	216	242	259	282
× 82	651	145	173	193	221	247	264	288
× 89	695	146	176	195	223	250	267	292
× 98	770	140	173	191	221	249	268	295
533 × 210 × 82	730	172	205	224	255	283	302	329
× 92	840	173	209	228	260	290	310	339
× 101	904	175	211	231	263	295	315	345
× 109	974	172	209	229	264	297	317	349
× 122	1105	165	206	227	263	299	321	356
610 × 229 × 101	1023	200	240	261	297	332	354	387
× 113	1134	203	243	266	304	341	364	399
× 125	1269	192	236	268	301	341	366	404
× 140	1430	190	238	272	306	349	374	415
610 × 305 × 149	1577	176	228	274	303	350	366	384
× 179	1905	157	188	249	280	329	372	372
× 238	2572	106	106	116	166	226	290	338

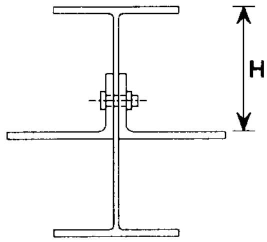
Notes for Tables 2 and 3 *(continued)*:

- *H* is the highest permitted position of the upper surface of the horizontal leg of the angle, as measured from the top of the beam to the upper face of the angle. Hence the exposed depth of the section is given by subtracting *H* from the section depth and adding the angle thickness.

Table 4 *Design table for shelf angle floor beams in fire*

Fire Resistance	60 mins

Beam Grade	Fe430
Angle Grade	Fe510



Section size	M_p (kNm)	H (mm), the position of the angle below top of beam for load ratio of:						
		0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	93	119	134	149	162	175	187	198
× 28	112	127	143	157	171	184	196	208
× 33	132	135	150	165	179	192	204	217
305 × 127 × 37	149	136	151	165	178	192	204	211
× 42	168	141	156	170	184	197	207	217
× 48	194	148	163	177	192	206	213	226
305 × 165 × 40	172	139	154	169	178	192	205	212
× 46	199	145	161	175	185	199	208	220
× 54	232	155	172	179	195	210	216	230
356 × 127 × 33	148	149	166	182	197	212	226	239
× 39	180	157	174	191	206	221	236	250
356 × 171 × 45	213	162	179	196	213	222	237	249
× 51	246	169	187	205	218	231	248	254
× 57	277	176	196	215	223	241	255	264
× 67	333	191	212	225	240	259	264	282
406 × 140 × 39	198	175	194	212	230	245	261	277
× 46	244	184	204	223	241	259	277	288
406 × 178 × 54	288	191	212	232	252	261	280	296
× 60	328	201	222	244	264	274	293	300
× 67	370	211	233	255	266	285	302	312
× 74	414	220	244	267	276	297	305	324
457 × 152 × 52	301	209	232	253	274	294	314	328
× 60	353	219	243	267	288	310	332	340
× 67	396	228	253	277	299	322	336	352
× 74	430	236	262	286	309	332	341	363
× 82	477	245	272	296	320	342	354	373
457 × 191 × 67	405	229	253	278	301	311	333	340
× 74	456	241	266	291	305	325	343	355
× 82	504	250	276	302	313	337	345	368
× 89	534	256	284	310	321	345	353	377
× 98	591	267	295	313	333	352	366	390
533 × 210 × 82	565	278	307	336	361	376	402	411
× 92	651	295	325	355	368	396	408	432
× 101	694	303	334	364	378	406	416	444
× 109	748	310	343	371	388	413	427	455
× 122	849	325	358	375	404	417	445	474
610 × 229 × 101	793	335	369	402	420	450	466	492
× 113	871	349	384	418	435	467	480	511
× 125	974	362	400	429	452	475	499	531
× 140	1099	378	416	435	470	484	518	550
610 × 305 × 149	1212	384	424	439	476	513	548	---
× 179	1463	408	433	465	504	542	578	---
× 238	1976	438	458	502	543	583	---	---

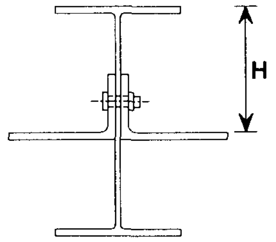
Notes for Tables 4 and 5:

- M_p is the moment capacity (cold) of the Universal Beam which forms the shelf angle beam.
- The maximum load ratio that may be sustained in fire for the design conditions is tabulated. Hence the moment capacity in fire is M_p × Load ratio. *(continued)*

Table 5 *Design table for shelf angle floor beams in fire*

Fire Resistance	60 mins

Beam Grade	Fe510
Angle Grade	Fe510



Section size	M_p (kNm)	*H* (mm), the position of the angle below top of beam for load ratio of:						
		0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 x 102 x 25	120	129	144	158	172	184	196	208
x 28	145	137	152	167	180	193	205	217
x 33	170	144	159	174	188	201	214	227
305 x 127 x 37	192	145	160	174	188	202	209	222
x 42	217	150	166	181	196	207	216	230
x 48	251	158	174	190	206	212	227	235
305 x 165 x 40	222	149	166	174	189	204	210	224
x 46	257	159	175	183	200	208	220	235
x 54	300	171	179	196	211	218	234	249
356 x 127 x 33	192	158	175	191	207	221	236	248
x 39	232	166	184	201	218	234	250	257
356 x 171 x 45	275	173	192	211	219	236	249	259
x 51	318	184	204	218	231	249	255	272
x 57	358	194	214	223	242	255	267	284
x 67	430	211	225	241	260	267	287	305
406 x 140 x 39	256	185	204	223	241	259	276	284
x 46	315	196	218	239	258	278	288	304
406 x 178 x 54	372	207	229	251	261	281	296	307
x 60	424	219	243	264	275	296	303	323
x 67	478	230	254	266	287	302	315	336
x 74	534	241	265	276	299	307	328	350
457 x 152 x 52	388	224	248	271	293	315	328	344
x 60	456	238	263	287	310	332	343	363
x 67	512	247	273	298	322	336	355	366
x 74	560	257	283	308	333	343	366	374
x 82	621	266	294	319	342	355	373	387
457 x 191 x 67	522	248	275	300	311	335	343	366
x 74	588	261	288	305	326	343	359	382
x 82	651	271	299	312	337	347	371	395
x 89	695	279	308	320	347	356	381	405
x 98	770	290	313	332	352	369	394	419
533 x 210 x 82	730	299	330	360	374	402	412	439
x 92	840	317	349	366	394	408	434	462
x 101	904	326	359	375	405	417	446	474
x 109	974	335	368	384	413	427	457	485
x 122	1105	349	375	399	417	444	474	503
610 x 229 x 101	1023	357	394	420	446	466	491	522
x 113	1134	373	410	429	464	479	511	543
x 125	1269	388	426	446	475	497	530	563
x 140	1430	402	433	462	479	514	548	581
610 x 305 x 149	1577	414	432	472	510	547	---	---
x 179	1905	433	455	496	535	573	---	---
x 238	2572	446	484	528	569	---	---	---

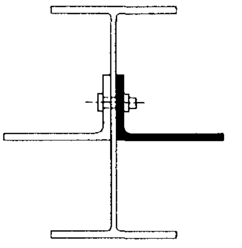
Notes for Tables 4 and 5 *(continued)*:

- *H* is the highest permitted position of the upper surface of the horizontal leg of the angle, as measured from the top of the beam to the upper face of the angle. Hence the exposed depth of the section is given by subtracting *H* from the section depth and adding the angle thickness.

Table 6 *Angle connection force*

Fire Resistance	30 mins

Beam Grade	Fe430
Angle Grade	Fe510



Section Size	Load (kN) in each angle to be resisted by bolts or welds of a load ratio of:						
	0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	105	105	106	119	132	143	153
× 28	124	124	130	145	158	170	181
× 33	140	140	151	167	182	195	208
305 × 127 × 37	162	162	179	195	200	215	229
× 42	175	177	197	215	218	235	251
× 48	193	198	220	241	244	263	281
305 × 165 × 40	191	193	209	224	228	243	256
× 46	209	211	230	247	249	266	282
× 54	232	236	258	278	280	299	318
356 × 127 × 33	137	151	167	181	195	200	213
× 39	160	178	196	212	228	233	248
356 × 171 × 45	202	207	227	246	262	268	285
× 51	226	230	252	273	291	296	314
× 57	246	246	271	294	304	320	341
× 67	286	286	315	342	348	371	395
406 × 140 × 39	168	188	206	223	233	245	259
× 46	197	220	241	260	268	284	302
406 × 178 × 54	242	266	272	294	315	323	343
× 60	264	290	291	316	339	344	367
× 67	284	314	317	345	371	376	402
× 74	313	345	348	379	408	413	441
457 × 152 × 52	224	251	275	297	308	326	345
× 60	244	275	302	328	338	356	379
× 67	265	300	331	359	370	391	417
× 74	285	321	354	384	394	418	445
× 82	295	337	374	407	418	445	475
457 × 191 × 67	293	323	325	355	382	389	414
× 74	316	350	353	385	415	421	449
× 82	343	380	383	418	450	456	487
× 89	356	395	399	435	469	475	508
× 98	362	407	408	450	489	497	534
533 × 210 × 82	344	383	389	424	458	490	498
× 92	383	426	433	471	508	523	552
× 101	402	446	454	493	532	547	577
× 109	413	462	474	512	555	572	586
× 122	425	484	504	539	586	586	586
610 × 229 × 101	415	465	484	516	558	586	586
× 113	448	499	521	553	586	586	586
× 125	456	515	569	573	586	586	586
× 140	484	551	586	586	586	586	586
610 × 305 × 149	514	583	586	586	586	586	651
× 179	508	539	586	586	586	586	651
× 238	332	332	351	396	506	586	586

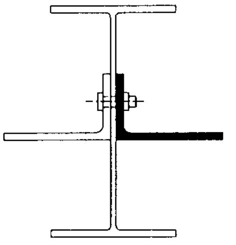
Note:

The table provides the total longitudinal force transferred to each angle along half the span of the beam. This force is then used to determine the number of connecting bolts or the weld size.

Table 7 *Angle connection force*

Fire Resistance	30 mins

Beam Grade	Fe510
Angle Grade	Fe510



Section Size	Load (kN) in each angle to be resisted by bolts or welds for a load ratio of:						
	0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	130	132	149	164	178	191	203
× 28	152	159	177	194	209	224	230
× 33	172	182	202	221	238	254	260
305 × 127 × 37	199	214	235	241	260	278	295
× 42	214	232	256	259	281	302	310
× 48	234	257	284	287	312	335	341
305 × 165 × 40	236	252	271	276	295	312	319
× 46	257	274	296	299	320	340	346
× 54	283	303	329	331	357	380	383
356 × 127 × 33	181	201	220	237	245	260	275
× 39	209	233	254	274	281	300	317
356 × 171 × 45	248	269	293	315	322	343	363
× 51	276	296	323	347	352	376	398
× 57	296	315	346	373	378	405	430
× 67	339	363	398	430	435	466	495
406 × 140 × 39	222	245	267	287	295	314	332
× 46	256	284	309	332	340	362	383
406 × 178 × 54	309	316	346	373	399	408	432
× 60	336	342	370	400	428	435	462
× 67	360	367	400	434	466	473	504
× 74	393	397	437	474	487	517	551
457 × 152 × 52	288	320	349	376	386	411	435
× 60	312	349	382	413	418	448	476
× 67	336	378	416	450	457	490	521
× 74	363	407	446	483	490	525	558
× 82	375	425	469	510	518	557	586
457 × 191 × 67	370	386	410	446	479	486	518
× 74	398	419	443	482	518	526	561
× 82	430	449	479	521	560	568	586
× 89	448	471	501	545	586	586	586
× 98	455	509	512	563	586	586	586
533 × 210 × 82	431	479	483	528	570	580	586
× 92	478	530	535	585	586	586	586
× 101	503	557	564	586	586	586	586
× 109	515	575	581	586	586	586	586
× 122	529	586	586	586	586	586	586
610 × 229 × 101	516	576	582	586	586	586	586
× 113	559	586	586	586	586	586	586
× 125	568	586	586	586	586	586	586
× 140	586	586	586	586	586	586	586
610 × 305 × 149	586	586	586	586	586	651	651
× 179	586	586	586	586	586	651	651
× 238	389	389	439	464	586	586	586

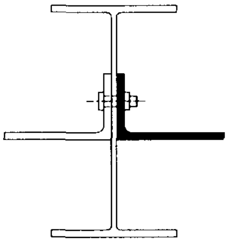
Note:

The table provides the total longitudinal force transferred to each angle along half the span of the beam. This force is then used to determine the number of connecting bolts or the weld size.

Table 8 *Angle connection force*

Fire Resistance	60 mins

Beam Grade	Fe430
Angle Grade	Fe510



Section Size	Load (kN) in each angle to be resisted by bolts or welds for a load ratio of:						
	0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	113	124	134	144	153	162	169
× 28	143	154	165	175	184	194	202
× 33	170	182	194	205	215	224	234
305 × 127 × 37	196	209	221	231	243	253	260
× 42	221	235	247	259	261	281	287
× 48	253	261	261	261	261	287	287
305 × 165 × 40	235	246	257	263	274	283	289
× 46	261	261	287	287	287	318	318
× 54	261	261	287	287	287	318	318
356 × 127 × 33	174	186	198	209	218	228	238
× 39	212	225	238	250	261	261	261
356 × 171 × 45	252	261	261	261	287	287	318
× 51	261	261	261	287	287	287	318
× 57	261	261	261	287	287	318	318
× 67	261	261	287	287	287	318	318
406 × 140 × 39	211	225	239	252	261	261	261
× 46	260	261	261	261	261	261	287
406 × 178 × 54	261	261	261	261	287	287	318
× 60	261	261	261	287	287	287	318
× 67	261	261	261	287	287	318	318
× 74	261	261	261	287	287	318	318
457 × 152 × 52	261	261	261	261	261	261	287
× 60	261	261	261	261	261	261	287
× 67	261	261	261	261	261	287	287
× 74	261	261	261	261	261	287	287
× 82	261	261	261	261	287	287	318
457 × 191 × 67	261	261	261	261	287	287	318
× 74	261	261	261	287	287	318	318
× 82	261	261	261	287	287	318	318
× 89	261	261	261	287	287	318	318
× 98	261	261	287	287	318	318	318
533 × 210 × 82	261	261	261	287	287	287	318
× 92	261	261	261	287	287	318	318
×101	261	261	261	287	287	318	318
×109	261	261	287	287	318	318	318
×122	261	261	287	287	318	318	318
610 × 229 × 101	261	261	261	287	287	318	318
× 113	261	261	261	287	287	318	318
× 125	261	261	287	287	318	318	318
× 140	261	261	287	287	318	318	318
610 × 305 × 149	287	287	318	318	318	318	---
× 179	287	318	318	318	318	318	---
× 238	287	318	318	318	318	---	---

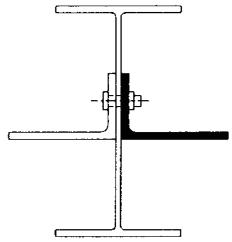
Note:

The table provides the total longitudinal force transferred to each angle along half the span of the beam. This force is then used to determine the number of connecting bolts or the weld size.

Table 9 *Angle connection force*

Fire Resistance	**60 mins**

Beam Grade	**Fe510**
Angle Grade	**Fe510**



Section Size	Load (kN) in each angle to be resisted by bolts or welds for a load ratio of:						
	0.4	0.45	0.5	0.55	0.6	0.65	0.7
305 × 102 × 25	149	162	175	186	197	207	217
× 28	185	199	212	224	236	246	257
× 33	218	233	247	260	261	261	261
305 × 127 × 37	249	261	261	261	261	287	287
× 42	261	261	261	261	287	287	287
× 48	261	261	261	261	287	287	318
305 × 165 × 40	261	261	287	287	287	318	318
× 46	261	287	287	287	318	318	318
× 54	261	287	287	318	318	318	318
356 × 127 × 33	223	238	252	261	261	261	287
× 39	261	261	261	261	261	261	287
356 × 171 × 45	261	261	261	287	287	318	318
× 51	261	261	287	287	287	318	318
× 57	261	261	287	287	318	318	318
× 67	261	287	287	318	318	318	318
406 × 140 × 39	261	261	261	261	261	261	287
× 46	261	261	261	261	261	287	287
406 × 178 × 54	261	261	261	287	287	318	318
× 60	261	261	287	287	287	318	318
× 67	261	261	287	287	318	318	318
× 74	261	261	287	287	318	318	318
457 × 152 × 52	261	261	261	261	261	287	287
× 60	261	261	261	261	287	287	318
× 67	261	261	261	261	287	287	318
× 74	261	261	261	261	287	287	318
× 82	261	261	261	287	287	318	318
457 × 191 × 67	261	261	261	287	287	318	318
× 74	261	261	287	287	318	318	318
× 82	261	261	287	287	318	318	318
× 89	261	261	287	287	318	318	318
× 98	261	287	287	318	318	318	318
533 × 210 × 82	261	261	261	287	287	318	318
× 92	261	261	287	287	318	318	318
× 101	261	261	287	287	318	318	318
× 109	261	261	287	318	318	318	318
× 122	261	287	287	318	318	318	318
610 × 229 × 101	261	261	287	287	318	318	318
× 113	261	261	287	287	318	318	318
× 125	261	261	287	318	318	318	318
× 140	261	287	287	318	318	318	318
610 × 305 × 149	287	318	318	318	318	---	---
× 179	318	318	318	318	318	---	---
× 238	318	318	318	318	---	---	---

Note:

The table provides the total longitudinal force transferred to each angle along half the span of the beam. This force is then used to determine the number of connecting bolts or the weld size.

Table 10 *Transverse bending and angle connection design table*

Aspect Ratio	Period of fire resistance					
	30 minutes			60 minutes		
	M_{cf}	θ_w	θ_b	M_{cf}	θ_w	θ_b
$D_e/B_e \leq 9.6$	8.46	205	278	1.92	535	655
$0.6 < D_e/B_e \leq 0.8$	7.43	240	313	1.63	545	665
$0.8 < D_e/B_e \leq 1.1$	6.26	280	352	1.39	560	680
$1.1 < D_e/B_e \leq 1.5$	6.26	280	352	1.39	560	680
$1.5 < D_e/B_e$	6.26	280	352	1.39	560	680

Key to table:

- D_e Exposed depth of steel
- B_e Width of bottom flange
- M_{cf} Transverse bending strength (kNm/metre)
- θ_w Design temperature for welds (°C)
- θ_b Design temperature for bolts (°C)

Table 11 *Block temperatures (Table 18 of BS 5950: Part 8)*

Aspect Ratio	Period of Fire Resistance					
	30 minutes			60 minutes		
	θ_2	θ_3	θ_R	θ_2	θ_3	θ_R
$D_e/B_e \leq 0.6$	$\theta_1 - 140$	475	350	$\theta_1 - 90$	725	600
$0.6 < D_e/B_e \leq 0.8$	$\theta_1 - 90$	510	385	$\theta_1 - 60$	745	620
$0.8 < D_e/B_e \leq 1.1$	$\theta_1 - 45$	550	425	$\theta_1 - 30$	765	640
$1.1 < D_e/B_e \leq 1.5$	$\theta_1 - 25$	550	425	θ_1	765	640
$1.5 < D_e/B_e$	θ_1	550	425	θ_1	765	640

Key to table:

- θ_1 Bottom flange temperature (°C)
- θ_2 Modified bottom flange temperature (°C)
- θ_3 Exposed angle temperature (°C)
- θ_R Angle root temperature (°C)

Table 12 *Temperature gradient (Table 19 of BS 5950: Part 8)*

Period of fire resistance	30 minutes	60 minutes
Temperature gradient, G	2.3	3.8

7. DESIGN EXAMPLE

The Steel Construction Institute Silwood Park Ascot Berks SL5 7QN Telephone:(0344) 23345 Fax:(0344) 22944 CALCULATION SHEET	Job No. *BCF 4880*		Sheet *1* of *5*		Rev.
	Job Title *Fire Resistance of Shelf Angle Floor Beams*				
	Subject *Design Example*				
	Client *B.S.*	Made by *GMN*		Date *Feb 1993*	
		Checked by *BKC*		Date *Feb 1993*	

Beam Span 7.2 metres

Beam Centres 6.0 metres

Beam 533 × 210 × 82 UB Grade 430

Fire Resistance 30 minutes

Loading:

Imposed 4.0 kN/m^2

Dead 4.5 kN/m^2

Load Factors for fire limit state

Imposed 0.8 } BS 5950: Part 8 Clause 3.1

Dead 1.0 }

Moment capacity for normal design is 566 kNm

Fire Limit State Moment

$$M_f = \frac{7.2^2 \times 6}{8} (0.8 \times 4 + 1.0 \times 4.5)$$

$$= 299.4 \text{ kNm}$$

$$\text{Load ratio} = \frac{299.4}{566} = 0.53$$

From Table 2 for 533 × 210 × 82 UB:

Load ratio	0.55	0.50
H (mm), Position of angle below top of beam	244	215

∴ *For load ratio of 0.53, H = 232 mm (by linear interpolation)*

Thus the upper surface of the angles must be positioned not less than 232 mm below the upper surface of the beam.

TRANSVERSE BENDING OF ANGLE

The bending moment will depend on the exact details selected and the assumed centre of the applied load. For fire, it is reasonable to assume that the load acts 10 mm in from the end of the precast unit. The clearance between the end of the unit and the upstand of the angle will be approximately 40 mm giving a lever arm of 50 mm.

Reaction/metre, R

$$R = \frac{6}{2} \times (0.8 \times 4 + 1.0 \times 4.5)$$
$$= 23.1 \text{ kN/m}$$

Transverse bending on angle, M

$$M = 50 \times 23.1 \times 10^{-3} \text{ kNm/m}$$
$$= 1.155 \text{ kNm/m}$$

The bending capacity of the angle is given by:

$$M_{cf} = 1.2\, p_y\, Z\, k_R \quad \text{(see Section 4, condition (f))}$$

The bending capacity may be obtained directly from Table 10. However, to illustrate the derivation of the table the full calculation is presented here.

$$Z = t^2/6$$

$$= \frac{12^2}{6} \times 1000 \text{ mm}^3/\text{m}$$

$$= 24000 \text{ mm}^3/\text{m}$$

The temperature of the exposed flange of the angle is obtained from BS 5950: Part 8, Table 18. This Table is reproduced here as Table 11.

$$D_e = (528.3 - 232) = 296.3 \text{ mm}$$
$$B_e = 208.7 \text{ mm}$$
$$D_e/B_e = 1.42$$

$\therefore$ *From Table 11 the exposed flange temperature,* θ_3 *, is 550°C.*

The strength reduction factor is obtained from BS 5950: Part 8, Table 1 at 1.5% strain. This is reproduced here as Table 1.

$k_R \quad = \quad 0.612$

For grade 510 steel, $p_y = 355\ N/mm^2$

$$\therefore M_{cf} = 1.2 \times 355 \times 24000 \times 0.612 \times 10^{-6}$$
$$= 6.26\ kNm/m$$

<u>Transverse bending is therefore satisfactory.</u>

CONNECTION OF ANGLES

The angles may be bolted or welded to the beam. This connection must be able to transmit the vertical loads and the horizontal load induced by bending. In this example the vertical load is 23.1 kN/m, as calculated previously. The horizontal load is not as easily calculated (by hand) as it depends upon the position of the plastic neutral axis in fire. Whilst using the moment capacity method to calculate the angle positions (H) in Tables 2 to 5, the load in each angle was also calculated. This calculation took account of the neutral axis position and whether it fell within the depth of the angle. This load is given in Tables 6 to 9 where Table 6 corresponds to design Table 2, Table 7 to Table 3, Table 8 to Table 4 and Table 9 to Table 5. The temperature at which any weld or bolt must be assessed is given in Table 10.

For the design example:

Horizontal load	*410 kN (Table 6 - by linear interpolation)*
Weld temperature, θ_w	*280°C (Table 10)*
Bolt temperature, θ_b	*352°C (Table 10)*

The derivation of the temperatures is now given.

From Table 11 the temperature of horizontal leg of angle, θ_3 *, is 550°C. A linear reduction in temperature upwards from the angle root is assumed by the Code. The temperature gradient, G, is taken from Table 12.*

$\theta_x \quad = \quad \theta_R - G.x$

$\theta_R \quad = \quad 425°C$ *Table 11*

$G \quad = \quad 2.3°C/mm$ *Table 12 (Table 19, BS 5950: Part 8)*

At mid-height

$x \quad = \quad 31.5\ mm$

The average temperature is therefore 352°C. If it is assumed that the bolts are positioned at mid-height of the vertical leg will be at a this temperature(θ_b). Bolts are assumed to lose strength in a manner similar to welds.

Hence $k_R = 0.8 \times 0.825$ *(Table 1, 0.5% strain)*

$= 0.66$

Consider 20 mm diameter, grade 8.8 bolts.

Shear strength $= 0.66 \times 91.9$

$= 60.6\ kN$

Total effective load $= [410^2 + (23.1 \times 7.2 / 2)^2]^{½}$

(per half span) $= 419\ kN$

Thus a minimum of 7 bolts will be required per half full span making 14 bolts on the full span at a pitch of about 520 mm.

For welded construction BS 5950: Part 8 states that only weld above the angle may be used and that any weld below must be discounted. The weld temperature, θ_w , is taken to be the temperature at the top of the angle leg. A linear variation up the height of the angle is again assumed.

$x = 63\ mm$

Temperature, $\theta_w = 425 - (63 \times 2.3)$

$= 280°C$

The strength of weld is assumed to be 80% of the strength of steel based on 0.5% strain.

$k_R = 0.8 \times 0.865$ *(Table 1, 0.5% strain)*

$= 0.69$

Thus at 69% of normal design strength weld must be provided to transmit 410 kN over half the span (114 kN/m) and a vertical load of 23.1 kN/m.

Effective load on weld per metre of the beam length

$$= (114^2 + 23.1^2)^{1/2}$$

$$= 117 \text{ kN/m}$$

Consider a 4 mm continuous fillet weld. From BS 5950: Part 1 this may be assumed to have a strength of 215 N/mm².

$$\text{Strength/m} = \frac{4}{\sqrt{2}} \times 1000 \times 215 \times 10^{-3} \times 0.69$$

$$= 419 \text{ kN/m}$$

A 4 mm fillet weld is clearly more than adequate so an intermittent weld could be considered. Below the angle there should be occasional tack welds as weld exposed directly is not considered to contribute any strength.

8. COMPARISON WITH TESTS

At least 8 fire resistance tests have been carried on shelf angle floor beams and these are summarised in Table 13. The tests were on both grade 430 and 510 universal beams all with 125 × 75 × 12 grade 510 angles. The span in each case was 4.5 m, which is the standard span used for fire resistance tests. The angle position is measured from the top of the beam to the upper surface of the horizontal leg of the angle. The tests were carried out by British Steel Technical, Swinden Laboratories.

Table 13 *Summary of fire resistance tests on shelf angle floor beams*

Test	Section	Grade	Angle position (mm)	Load Ratio	Fire resistance (mins)
1	406 × 178 × 54	430	229	0.56	67
2	305 × 165 × 40	430	219	0.58	83
3	406 × 178 × 54	510	221	0.23	94
4	406 × 178 × 54	430	121	0.52	29
5	406 × 178 × 54	430	221	0.41	70
6	406 × 178 × 54	430	121	0.25	74
7	254 × 146 × 43	430	179	0.54	91
8	254 × 146 × 43	430	148	0.55	69

It is not possible to make a direct comparison between all the tests and the design tables but a reasonable comparison can be made for Tests 1, 4 and 8. These tests achieved fire resistances close to some of the tabulated design data. In Table 14, a comparison of both angle position and the temperature of the horizontal leg of the angle is shown. The temperature for the comparison is taken from BS 5950: Part 8, Table 18 which is reproduced on page 16 as Table 11.

Table 14 *Comparison of test results and design method*

Test	Section	Load Ratio	Fire resistance (mins)	Angle position (mm)		Angle temperature (°C)	
				Test	Tables	Test	Part 8
1	406 × 178 × 54	0.56	67	229	254†	824	765†
4	406 × 178 × 54	0.52	29	121	161*	571	550*
8	254 × 146 × 43	0.55	69	148	157†	843	745†

† Based on 60 minutes (Design Table 4)
* Based on 30 minutes (Design Table 2)

In each case the design method is conservative in that it results in lower angle positions with more of the beam being shielded from the fire. In Tests 1 and 4 the predicted temperature of the angle, making allowances for the small time differences, compares well with the measured temperatures. In Test 4 the design temperature is somewhat conservative. As stated earlier, more exact calculation methods exist which would give results closer to those achieved in the tests but these are very complex and beyond the scope of BS 5950: Part 8.

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