A Safe and Economical Design of Composite Profile Steel Decking Systems under Fire Conditions

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Abstract

Due to two fire incidents viz. the Basingstoke and the Broadgate Fires, composite slabs consisting of steel beams and lightly reinforced concrete slabs with steel decking showed an inherent load-carrying capacity in fire by mobilizing tensile membrane action at large displacements. Based on a number of research works on tensile membrane action of composite floor slabs, a design guide has been released in the UK in 2006, viz. SCI Publication P288, in which the BRE-Bailey method was adopted. This method allows interior secondary beams to be unprotected so that fire-protection costs can be reduced without compromising on structural safety. Many composite steel-framed buildings in the UK have since benefited from the application of the method, resulting in reduced fire protection costs for secondary steel beams.

An experimental programme including 8 composite beam-slab floor system specimens had been tested under fire conditions at Nanyang Technological University from 2010-2012 to investigate the assumptions and the validity of the Bailey-BRE method. It is concluded that the Bailey-BRE method is conservative and SCI P288 can be applied in Singapore without compromising safety of steel-framed composite structures providing that detailing of structural members should be followed closely in the construction phase.

Keywords: Tensile membrane action; Slab-beam systems; Restraint; Composite slabs; Fire

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1 Introduction

Large-scale fire tests, as well as well-publicised accidental building fires over the past two decades, have shown that under fire conditions composite slabs consisting of steel beams and lightly reinforced concrete slabs with steel decking possess a significant load-bearing capacity, which can be well above that predicted by the conventional yield-line theory. This load-carrying mechanism has been defined as tensile membrane action (TMA), which can be mobilized in the composite slabs at large displacements, irrespective whether the slabs are restrained horizontally or not.

Bailey and Moore (2000) have developed a new design method for composite slabs under fire conditions, namely, the Bailey-BRE method. This method allows interior secondary beams to be unprotected so that the fire-protection costs can be reduced. This method has been adopted in SCI Publication P288 (Newman et al., 2006) and applied in the UK practice in the recent years.

SCI Publication P288 sets out the design philosophy for the Bailey-BRE method, while SCI Publication P390 (Simms and Bake, 2010) provides the information on the use of TSLAB software v3.0 and an update for some parts of P288. This software has been developed by SCI to facilitate the application of the Bailey-BRE method. P288 has been developed based on extensive fire test results, ambient temperature tests and finite element analyses. P390 has incorporated Eurocode requirements and included verification for the protected edge beam capacity. Both P288 and P390 must be used together when applying the Bailey-BRE method to design steel-framed buildings with composite slabs. Many buildings in the UK have since benefited from the application of the simple design method, resulting in reduced fire protection costs.

The Bailey-BRE method assumes that vertical supports along the slab panel boundaries at all times during a fire do not deform and are provided by the protected edge beams with sufficient rigidity and strength during the fire. However, in reality, the deflection of the edge beams may be considerable and thus this assumption may be unrealistic. Additionally, all previous experimental studies focussed on isolated slabs rather than on the behaviour of connected floor assemblies. The question arises whether the method can be applied for composite beam-slab systems with deflecting edge beams.

Therefore, a fairly extensive test programme has been conducted in Nanyang Technological University, Singapore (NTU) from 2009 to 2012 to study the assumptions and validity of the Bailey-BRE method. This paper first discusses in detail the shortcomings of

the Bailey-BRE method, and then presents the calibration of P288 and P390 against the NTU fire tests.

2 SCI Publication P288 and P390

2.1 Discussions on the Bailey-BRE method

The Bailey-BRE method begins by dividing a composite floor system into several horizontally-unrestrained, vertically supported slab panels – *floor design zones*. Each of these floor design zones consists of simply-supported unprotected interior beams. As temperature increases, the formations of plastic hinges in the interior beams re-distribute the load to the two-way bending slab which undergoes large vertical deflections. Based on rigid-plastic theory with large change of geometry, the additional slab capacity provided by TMA is calculated as an enhancement to the small-deflection conventional yield-line capacity of the concrete slab panel.

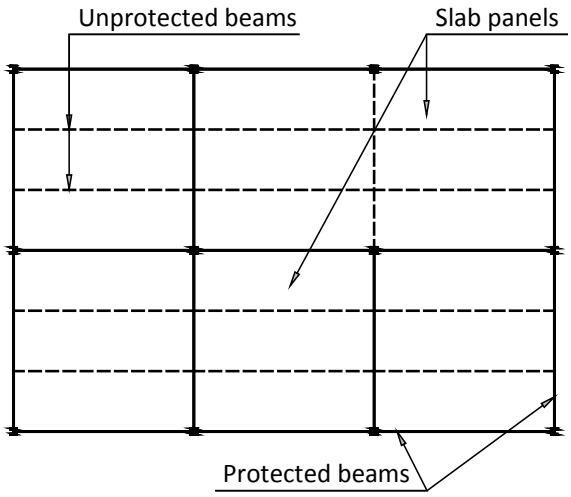


Fig. 1 Typical slab panels

The Bailey-BRE method assumes that the slab panel is simply supported irrespective of geometric configurations, and the edges are unrestrained horizontally. This implies that TMA is formed in the central region of the slab and a compressive ring is formed around the perimeter of the slab. Based on the authors' tests conducted at NTU (Nguyen and Tan, 2012), it is shown that in all the tests steel mesh had been fractured above the edge beams of the slab. Therefore, this assumption is valid.

The most controversial assumption is that vertical supports along the slab panel boundaries remain rigid at all times during a fire. To provide the necessary vertical support the edge beams of a slab panel must be protected to a required fire resistance. This is essential for the slab to bend into a two-way synclastic curvature. However, in reality, the edge beams

may deform considerably even though they are fire-protected, and thus this assumption may be nullified. This assumption is verified against the authors' test results and discussed in Section 4.

When calculating the contribution of unprotected interior beams to the total load-bearing capacity of the slab, Bailey treated these beams as composite beams. Under tensile membrane stage, since the load path has been changed from the slab via supporting edge beams to the columns, if the interior beams are treated as composite beams, the method may overestimate the total load capacity by taking into account twice the load supported by parts of concrete slab over the interior beams. The authors have checked this assumption and presented in Section 4.

In the simple design method a deflection limit has to be assumed, and then the enhancement above the yield-line capacity of the slab due to TMA can be computed based on that deflection. This deflection limit is estimated by combining the components due to thermal curvature and strain in the reinforcement.

$$w = \frac{\alpha (T_2 - T_1) l^2}{19.2 h_s} + \sqrt{\left(\frac{0.5 f_y}{E_a} \right)_{\text{Reinf}' t_{20^\circ\text{C}}} \frac{3L^2}{8}} < w_{\max} = \frac{\alpha (T_2 - T_1) l^2}{19.2 h_s} + \frac{l}{30} \qquad (1)$$

where α is the coefficient of thermal expansion (12×10^{-6} for normal weight concrete; T_2 and T_1 are the bottom and top surface temperatures of the slab, respectively; h_s is the slab thickness; l and L are the shorter and longer spans of the slab panel; f_y and E_a are the yield strength and the elastic modulus of the reinforcing steel at ambient temperature.

Based on the Cardington fire test, Bailey assumed that $(T_2 - T_1)$ is equal to 770°C for fire exposure below 90 minutes and 900°C thereafter. This value was obtained from the test data from the Cardington fire tests (Bailey et al., 1999) and referred hereafter as *the P288 deflection limit*.

In P390 (Simms and Bake, 2010), an updated version of P288, the deflection limit is also calculated by Eq. (1), except that the term $(T_2 - T_1)$ is based on the temperatures calculated at the bottom and top surfaces of the slab at each time step (referred hereafter as *the P390 deflection limit*). The difference between the two deflection limits highlights the effect of recent changes to the Bailey-BRE method (Bailey and Toh, 2007).

The two deflection limits, i.e. P288 and P390 deflection limits, are compared with the actual test results at ultimate limit state to see if they are conservative.

2.2 Type of structure

It is important to note that SCI P288 and P390 shall not be used to replace SS EN 1994-1-1:2004 and SS EN 1994-1-2:2005. They only provide design guidance on an advanced calculation method in design of composite steel-framed buildings to reduce fire-protection costs.

The two documents SCI P288 and P390 **do not** apply to:

(1) Floors constructed using precast concrete slabs;
(2) Internal floor beams that have been designed to act non-compositely (beams at the edge of the floor slab may be non-composite);
(3) Beams with service openings, *i.e.* composite floor with cellular beams;
(4) Flat slab systems;
(5) Composite slabs that require above 2-hr fire resistance

Structural type (1) to (4) was proposed in SCI P288 and P390. Structural type (5) is based on the authors' experimental study in NTU.

3 Experimental Programme in Nanyang Technological University

The test programme conducted in NTU from 2010 to 2012 included two series with eight composite beam-slab floor systems in total, which were tested under fire conditions to study the development of tensile membrane action (TMA) in the composite beam-slab systems. Only brief information of the specimens is provided here. Details of the test results and discussions can be found in Nguyen and Tan (2014).

The specimens were of *one-quarter scale* due to limitations of laboratory facility and space. For interior slab panels, the slabs had an outstand of 0.45m around all four edges. Shrinkage reinforcement mesh with a grid size of 80mm x 80mm and a diameter of 3mm (giving a reinforcement ratio of 0.16%) was placed at about 38mm below the slab top surface. The 0.16% reinforcement ratio was close to the minimum value required by EN 1994-1-1 (0.2% for un-propped construction). The mesh was continuous across the whole slab, with no lapping of mesh. The specimens were cast using ready-mixed concrete, with the aggregate size ranging from 5 to 10 mm.

The edge and secondary beams were Class 1 sections according to EN 1993-1-1 (2005a). Fabricated sections were used for the unprotected interior beams, since there was no suitable Universal Beam section. Full-shear composite action between the slab and the down-stand beams was achieved by using shear studs of 40mm height and 13mm diameter.

All the edge beams and the columns were protected to one-hour rating. No fire-proofing material was applied to the interior beams and the slabs.

Table 1 summarises the details of the specimens. Among the eight specimens there were two without interior beams, namely, S1 and S3-FR. The others had two unprotected interior beams. Fig. 2 shows the specimens without unprotected interior beams, while Fig. 3 shows the specimens with two unprotected interior beams.

Table 1 Specimen details

Series		*L x W x h (mm)*	*Aspect ratio*	*Main beam*	*Protected secondary beam*	*Unprotected interior beam*
I	*S1*	2250x2250x55	1.0	W130x130x28.1	80x80x17.3	*n.a.*
	S2-FR-IB	2250x2250x55	1.0	W130x130x28.1	80x80x17.3	80x80x17.3
	S3-FR	2250x2250x58	1.0	W130x130x28.1	80x80x17.3	*n.a*
II	*P215-M1099*	2250x2250x57	1.0	W130x130x28.1	80x80x17.3	80x80x17.3
	P368-M1099	2250x2250x58	1.0	W130x130x28.1	100x80x18.8	80x80x17.3
	P486-M1099	2250x2250x55	1.0	W130x130x28.1	102x102x23	80x80x17.3
	P215-M1356	2250x2250x58	1.0	UB 178x102x19	80x80x17.3	80x80x17.3
	P215-M2110	2250x2250x59	1.0	UB 203x102x23	100x80x18.8	80x80x17.3

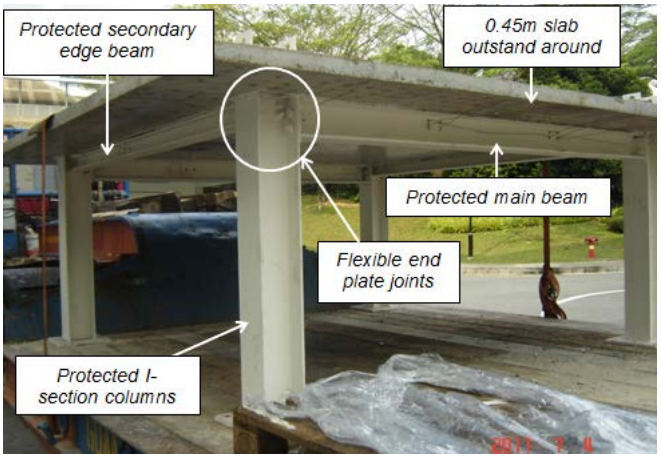


Fig. 2 Specimens without interior beams

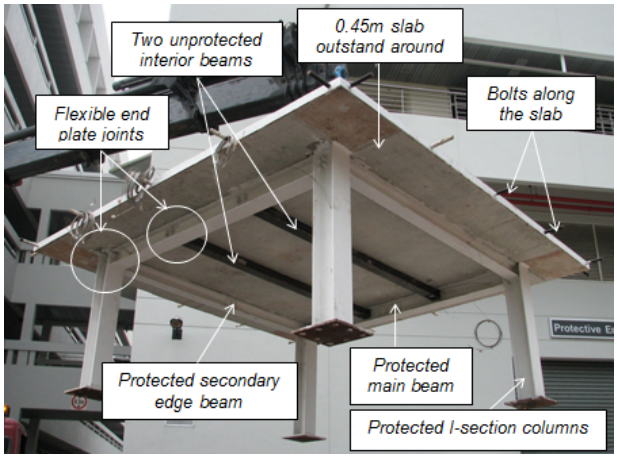


Fig. 3 Specimens with two unprotected interior beams

Fig. 4 shows a typical test setup. Due to the large dimensions of the furnace (3m long x 3m wide x 0.75m high), it could not simulate the ISO 834 standard fire curve. Its heating rate is about 20^0C/min, which is within the practical range of heating rate for steel sections as stipulated in BS 5950-8 (2003).

All the specimens were loaded up to a predetermined value of 15.8kN/m^2. This value

corresponded to 0.35 of the yield-line load at ambient temperature for specimens with interior beams and 2.0 for specimens without interior beams. After that, the load was kept constant and temperature was increased until failure was identified. This was the time when there was a significant drop in the mechanical resistance, and the hydraulic jack could no longer maintain the load level (violation of criterion "*R*").

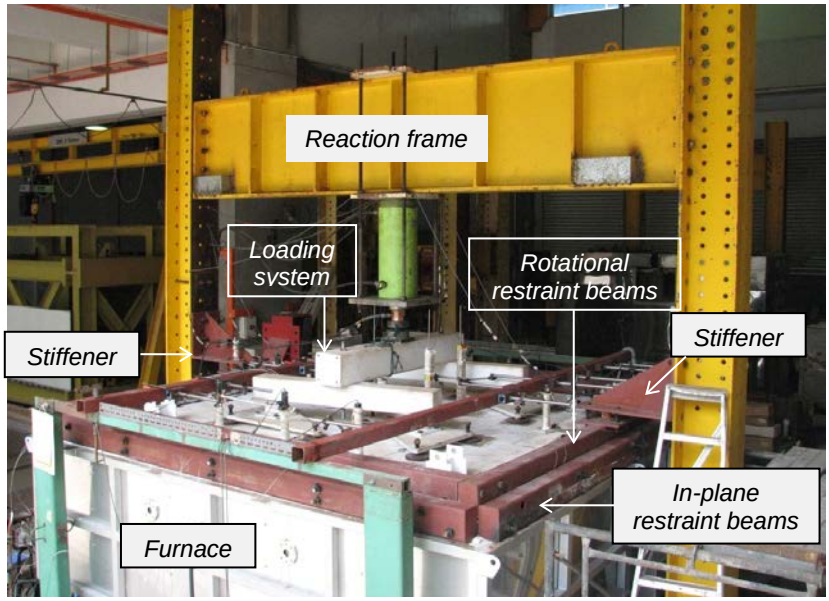


Fig. 4 Test setup

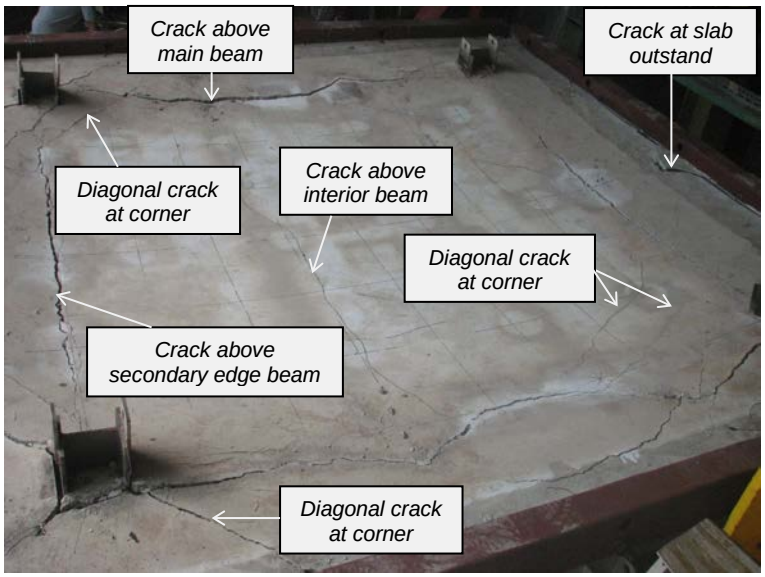


Fig. 5 Typical failure mode

Fig. 5 shows a typical crack pattern and the final failure mode of a specimen. The failure mode observed in all the tests was fracture of reinforcement in the slab close to the protected edge beams. As temperature increased, parallel cracks above the main and secondary edge beams opened widely and penetrated through the slab thickness, leading to reinforcement

fracture. No global collapse occurred. No premature failure at the shear studs and at the beam-column and beam-beam connections was observed.

4 Calibration of P288 and P390 against NTU fire tests

4.1 Principles

Verification of deflection limits

Fig. 6 shows typical test results of a specimen in which temperatures of the slab (bottom and top surfaces, and reinforcing mesh) were indicated together with the central deflection of the slab. Both deflection limits, i.e. P288 and P390 deflection limits, were calculated. The difference is in the term $(T_2 - T_1)$. For the P288 deflection limit, $(T_2 - T_1)$ is equal to 770°C for fire exposure below 90 minutes and 900°C thereafter. For the P390 deflection limit, T_2 and T_1 were determined based on the actual test results at failure. Comparisons between these two deflection limits and test results are presented in Section 4.2.1.

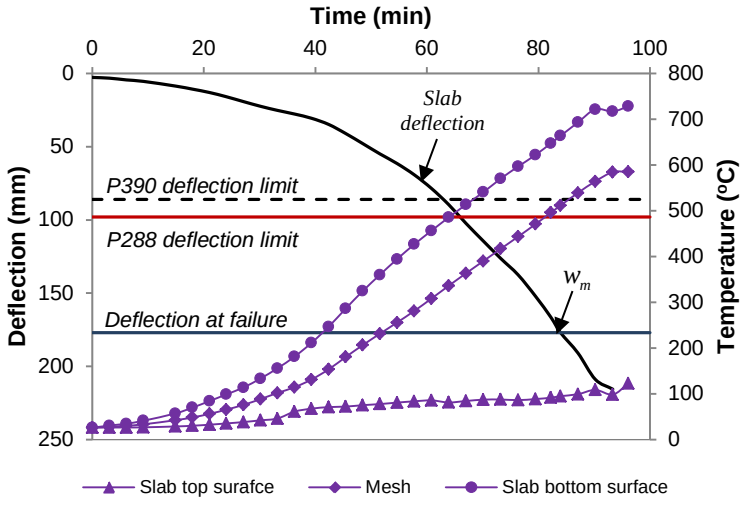


Fig. 6 Typical test results

Comparisons of load-bearing capacity for specimens without unprotected interior beams

Since the Bailey-BRE method does not consider deflection of edge beams, the enhancement factor predicted by P288 (e) is calculated using the relative slab deflection measured at failure and compared with the enhancement factor determined from the tests (e_{test}). The P288 and P390 deflection limits were not used for these comparisons since all the specimens failed at a deflection greater than the P288 and P390 deflection limits. Using a

greater deflection, a greater enhancement factor will be obtained. If the greater predicted enhancement factor is conservative, the smaller one is even more conservative.

The relative slab deflection from the tests can be calculated by Eq. (2).

$$\text{Relative slab deflection: } w_r = w_m - \frac{1}{4}\left(w_{MB1} + w_{MB2} + w_{PSB1} + w_{PSB2}\right) \qquad (2)$$

where w_m is the maximum slab deflection at failure; w_{MB1}, w_{MB2} are the deflection of two main edge beams corresponding to w_m; w_{PSB1}, w_{PSB2} are the deflection of two secondary edge beams corresponding to w_m.

For the specimens without unprotected interior beams, the comparison was straightforward. Based on the relative slab deflection Eq. (2), the enhancement factor was calculated and compared with that determined from the tests. The load-bearing capacity of the beam-slab systems without the interior beams is equal to $e \times p_{y,\theta}$ ($p_{y,\theta}$ is the yield load at failure temperature).

Comparisons of load-bearing capacity for specimens with unprotected interior beams

The Bailey-BRE method proposes that the load-carrying capacity of the composite unprotected interior beams and the slab (enhanced due to TMA) are added together provided that the unprotected interior beams have not failed yet. The load-carrying capacity of the beam-slab floor systems with the interior beams can be calculated using Eq. (3).

$$q_{t,\theta} = e \times p_{y,\theta} + p_{b,\theta} \qquad (3)$$

where $q_{t,\theta}$ is the total capacity of the slab at temperature θ; e is the enhancement factor; $p_{y,\theta}$ is the yield load at temperature θ; $p_{b,\theta}$ is the increase in the slab load capacity due to flexural strength of unprotected interior beams at temperature θ if these beams have not failed.

The load-carrying capacity of the composite unprotected interior beam refers to the bending moment resistance of the beam calculated by using I-steel section plus concrete flange on top of the steel section.

The authors have verified the assumption of using composite section of unprotected interior beams (Nguyen, 2014). It is found that when calculating part of the load supported by the unprotected interior beams, if the unprotected interior beams are ignored, the Bailey-BRE method is conservative. The comparison results are shown in Section 4.2.2.

In case of presence of interior beams, at the failure point the test load would be supported by tensile membrane action mobilised in the slab together with any residual flexural resistance of unprotected interior beams. Therefore, the steps used to validate the Bailey-BRE method against the specimens with interior beams are as follows:

- Check if the interior beams have failed yet using the bending moment capacity method in BS EN 1994-1-2 (2005b).
- If the beams had failed, the test load was totally resisted by the slab. The enhancement factor is calculated and compared with that determined from the test.
- If the interior beams had not failed yet, the load supported by the interior beams would be subtracted from the test load. The remainder load was used to calculate the actual enhancement factor and then compared to the predictions by P288.

4.2 Comparison results

4.2.1 Deflection limit

Table 2 shows the comparisons of the P288 and P390 deflection limits against the test results. It can be seen that the P288 deflection limit is conservative with an average ratio of prediction-to-test deflection of 0.77. The deflection limit from P390 is even more conservative with a value of 0.64.

Table 2 Comparisons of deflection limits against test results

Series	*Test*	h_s	*Deflection due to thermal curvature*	*Deflection due to mechanical strain*	*P288 deflection limit (Eq. (1))*	*P390 deflection limit*	*Max. deflection in test**	*P288 / Test*	*P390 / Test*
		mm	*mm*	*mm*	*mm*	*mm*	*mm*		
I	*S1*	55	44	54	98	80	131	0.75	0.61
	S2-FR-IB	55	44	54	98	86	177	0.55	0.49
	S3-FR	58	42	57	99	73	115	0.86	0.63
II	*P215-M1099*	57	43	57	99	84	124	0.80	0.68
	P368-M1099	58	42	57	99	88	118	0.84	0.74
	P486-M1099	55	52	57	108	90	139	0.78	0.65
	P215-M1356	58	42	57	99	91	121	0.81	0.75
	P215-M2110	59	48	57	105	83	143	0.74	0.58
							M =	**0.77**	**0.64**

** Test terminated when fracture of reinforcement had been identified.*

4.2.2 Load-bearing capacity

Table 3 shows that when calculating part of the load supported by the unprotected interior beams, if treating the interior beams as bare steel beams, the method proposed in SCI P288 is conservative. P288 gives a smaller prediction compared to the test results with 17.5% in average.

Table 3 Comparison of P288 predictions against test results

Series	*Test*	p_{test} kN/m^2	*MB def.* *mm*	*PSB def.* *mm*	*Slab def.* *mm*	*Relative def.* *mm*	*Total capacity* (kN/m^2) *(Eq. 2)*	*Prediction / Test (Eq. 2)*
I	*S1**	15.6	28	58	131	88	13.1	0.84
	S2-FR-IB	15.1	56	84	177	107	10.4	0.69
	*S3-FR**	16.0	33	28	115	85	14.6	0.92
							***M* =**	**0.82**
II	*P215-M1099*	15.6	38	57	124	76	14.2	0.91
	P368-M1099	15.3	51	83	118	51	11.9	0.78
	P486-M1099	15.5	55	94	139	64	12.9	0.83
	P215-M1356	15.4	59	88	121	48	12.2	0.79
	P215-M2110	15.6	39	79	143	84	13.1	0.84
							***M* =**	**0.83**

** Specimens without interior secondary beams*

5 Conclusions

Based on the calibration of the Bailey-BRE method against two test series (8 composite beam-slab floor system specimens in total), it is concluded that the Bailey-BRE method is conservative and SCI P288 and P390 can be used with the following conditions:

(1) When calculating the slab enhancement factor, *the deflection limit proposed in SCI P390* should be used instead;

(2) When calculating the additional load-bearing capacity contributed by unprotected interior beams, the residual resistance of unprotected interior steel beams is very small and can be neglected at fire conditions.

(3) The required bending moment resistance of the edge beams must be checked by considering alternative yield line patterns that would allow the slab to fold along an axis of symmetry without developing TMA. Details of the calculation method are given in Section 2 of SCI P390. This procedure shall be followed.

It is important to note that the SCI Publications P288 and P390 shall not be used to replace SS EN 1994-1-1:2004 and SS EN 1994-1-2:2005 in the design of composite steel-frame buildings under fire conditions. They only provide design guidance on an advanced calculation method that engineers may use to reduce fire-protection costs. All detailing requirements of EN 1994-1-1 (2004) should be adhered to.

Acknowledgment

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