4th International Conference on Steel & Composite Structures
Wednesday 21 – Friday 23 July 2010
Sydney, Australia

A SIMPLIFIED DESIGN METHOD FOR COMPOSITE FLOOR BEAMS WITH WEB OPENINGS IN FIRE

V.Y. BERNICE WONG[1a], IAN W. BURGESS[1b], ROGER J. PLANK[2]

[1] *Department of Civil and Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK*
[a]v.wong@sheffield.ac.uk, [b]ian.burgess@sheffield.ac.uk
[2] *School of Architectural Studies, University of Sheffield, Sheffield S10 2TN, UK*
r.j.plank@sheffield.ac.uk

ABSTRACT

A finite element investigation into the behaviour, including local instabilities, of cellular composite members subjected to elevated temperatures has been conducted, considering material and geometrical non-linearities. Close correlation has been observed between the finite element results and data from a full scale fire test. The study has been extended to develop a simplified design method for composite floor beams with regular web-openings subjected to fire. The approach predicts the capacity and failure type of a composite member by applying design criteria for each of the possible failure modes at successive cross-sections of the member at normal and elevated temperatures; a limiting temperature of the section as a whole is calculated. Predictions from the proposed simplified model are compared with finite element and experimental results. The design model is seen to be in good but conservative agreement with these.

1. INTRODUCTION

Composite floor beams with regular web openings are currently being widely used in multi-storey building construction. The web openings, usually circular or rectangular, are often used to provide passage for utilities, and hence the overall building height is minimised. The distribution of material between the compressive concrete flange and the tensile steel flange is optimised to maximise the efficiency of the composite action, but this optimised form leads to questions being asked about unusual potential failure modes, particularly at elevated temperatures.

In practice, web-openings in a beam result in loss of strength, and significantly reduce the flexural capacity of the beam. A web opening produces an additional (Vierendeel) effect across the length of the opening due to the vertical shear forces at the ends of the opening. This can result in the formation of four plastic hinges at the “corners” of an opening. Equally, shear forces transferred across the web-posts between openings can result in local buckling of these web-posts. In the event of fire, the rapid loss of strength and stiffness of structural steel will significantly influence the capacities of the composite perforated section.

Current UK design practice for composite floor beam with web openings is based on Steel Construction Institute (SCI) publications [1-2], as well as theoretical guidelines based on previous research studies [3-6]. These methods provide design guidance for composite and non-composite cellular floor beams, particularly at ambient temperature. In recent years, the SCI has issued fire engineering design guidance [7] for composite beams with circular web openings. However, this guidance is limited to beams with circular web openings where web-post buckling is critical. In this paper, a simplified design method representing the Vierendeel mechanism for composite floor beams with rectangular web-openings in fire is developed. The simplified model is validated by comparing its predictions with a full scale experimental result. Theoretical results were also obtained by the finite element method for comparison, so that the accuracy of the developed method could be assessed.

2. ANALYTICAL MODEL

Based on the available design guides [1- 6] for ambient temperature, an analytically-based model has been developed to determine critical temperatures, taking into account shear force transfer by Vierendeel action across the openings and the forces generated across web-posts. The high-temperature limiting cases of the composite beam are assessed by applying the appropriate material properties. In this paper the Vierendeel effect is particularly addressed, since the full-scale test was designed to induce this type of failure.

2.1. Restrictions on size and position of openings

The general SCI guidance [1] provides the following constraints on the size and position of web openings. If D is the overall depth and L is the span of the beam:

Opening position:	Depth of the upper-tee and lower-tee sections should not differ by more than a factor of 2.
Width of end-post:	Width of end-post should not less than $2D$ or $0.1L$.
Spacing of openings:	The distance between adjacent openings should not be less than D.
Opening size:	The opening length and height should not exceed $1.5D$ and $0.6D$ respectively in unstiffened sections.

2.2. Influence of shear connection

The resistance to the applied Vierendeel moment across an opening depends on composite action of the upper-flange section and concrete slab. Where partial shear connection exists, the force in the concrete slab (N_c) is limited by the number of shear connectors placed between the support and the centre of the opening (n_{sc}).

$$N_c = n_{sc} P_{Rd} \tag{1}$$

Where P_{Rd} is the design resistance of a shear connector. In fire design this should be defined as the lesser of:

$$P_{Rd,\theta} = 0.8 k_{u,\theta} \left(0.8 f_{u,\theta} \left(\frac{\pi d^2}{4} \right) \Big/ \gamma_{v,fi} \right) \tag{2}$$

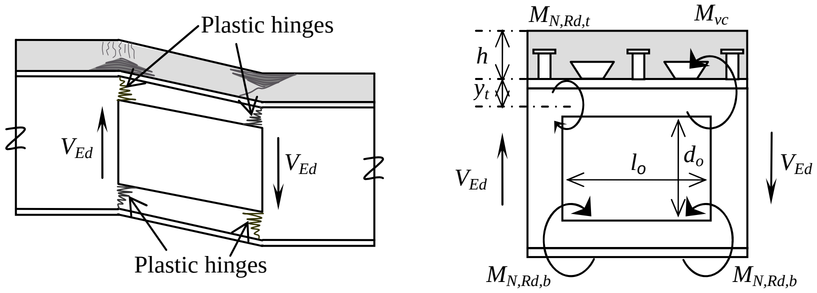
$$P_{Rd,\theta} = k_{c,\theta} \left(\frac{0.29 d^2 \left(f_{ck} E_{cm} \right)^{0.5}}{\gamma_{v,fi}} \right) \tag{3}$$

where:

$k_{u,\theta}$ is the strength retention factor for the ultimate strength of the steel according to [8]
$k_{c,\theta}$ is the strength retention factor for concrete according to [8]
$\gamma_{v,fi}$ is the partial material factor for fire design, taken as 1.0
d is the diameter of the shear connector

2.3. Vierendeel resistance

Transfer of shear across a web opening results in the formation of plastic hinges at its four “corners”. For a composite beam, the interaction between the concrete slab and the upper-flange of the steel beam tends to slide the concrete slab from the high-moment to the low-moment end. Thus composite action developed between the top-tee section and concrete slab significantly increases the resistance to Vierendeel bending.



(a) (b)

Figure 1: Vierendeel mechanism (a) Mode of failure; (b) Vierendeel bending around web opening.

In fire, the total Vierendeel resistance ($M_{v,Rd,fi}$) provided by the local plastic bending resistance at the four corners is defined as:

$$M_{v,Rd,fi} = M_{N,Rd,t,fi} + 2M_{N,Rd,b,fi} + M_{vc,fi} \tag{4}$$

$M_{N,Rd,t,fi}$ and $M_{N,,Rd,b,fi}$ are the plastic bending resistances of the top-tee and bottom-tee of the perforated steel section. These are reduced due to coincident tensile forces, according to the following approximate interaction equation:

$$M_{N,Rd,fi} = M_{Rd,fi}\left[1-\left(\frac{N_{Ed,fi}}{N_{Rd,fi}}\right)^2\right] \tag{5}$$

$M_{Rd,fi}$ is the local bending resistance of the tee. Plastic resistance should be used for Class 1 and 2 sections; elastic section properties are used for Class 3 and 4 sections.
$N_{ED,fi}$ is the axial compression or tension force due to the overall bending moment.
$N_{Rd,fi}$ is the axial resistance of the tee sections.

$M_{vc,fi}$ is the bending resistance of the sagging hinge due to local composite action between the top-tee section and the concrete slab. Its magnitude depends on the number of shear connectors placed directly above the opening. It may be approximated by:

$$M_{vc,fi} = n_{s,o} P_{Rd,fi} (h_c - \frac{x_c}{2} + y_t) \tag{6}$$

where:
$n_{s,o}$ is the number of shear connectors provided above the opening.
$P_{Rd,fi}$ is the design shear resistance of a shear connector at high temperatures.
h_c is the overall depth of the concrete slab.

x_c is the thickness of concrete in the compressive zone.
y_t is the distance of the neutral axis of the steel top-tee section from the top-flange.

The applied Vierendeel moment across the opening is equal to the applied shear force x length of opening (V_{ED} x l_o); where V_{Ed} is the design shear force.

3. EXPERIMENTAL MODEL

The test specimen was fabricated as a plate girder. The test span was 4.2m with five rectangular web-openings (Fig. 2). It was of asymmetric cross-section fabricated from steel plates of 200mm x 15mm (top flange), 250mm x 15mm (bottom flange) and 10mm x 370mm (web). The concrete slab was 120mm thick x 700mm wide, using C30 concrete with A142 reinforcing mesh and 1.2mm thick Metfloor 55 steel decking. Shear connectors 19mm diameter x 100mm long were used. The nominal yield strength of the steel beam was 275N/mm^2. As shown in Fig. 3, a total load of 140kN was applied to the top of the concrete slab via four point loads. The test was conducted in a 4m x 3m furnace, using an ISO 834 standard fire curve. The specimen was designed to demonstrate Vierendeel failure, as predicted by the simplified method. The loading was applied in successive increments at ambient temperature, and was maintained during the fire test.

Figure 2: Experimental setup: loads applied to beam

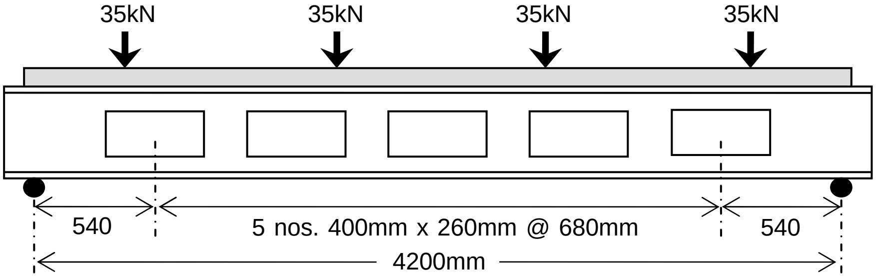


Figure 3: Geometric detail of symmetric composite cellular beam specimen

4. FINITE ELEMENT MODEL

The experimental model was analysed by ABAQUS [9], using a previously developed FE model [10], developed to analyse composite cellular beams of different geometries under a variety of loading and fire conditions.

A three-dimensional eight-noded solid element and four-noded quadrilateral shell elements with reduced integration were used in representing the concrete slab and cellular steel beam respectively. The material properties allocated to steel and concrete elements are based on their nominal properties. Reinforcing mesh in the solid slab element was defined as a layer of steel of equivalent area in each direction. Full composite action between the concrete slab and the cellular steel beam was assumed; this was achieved by using a tying constraint to tie the surfaces of both components together. The finite element meshes were chosen to facilitate the representation of the web openings. As the object of the analysis was to predict the overall behaviour of the model, an average refined mesh was used in order to reduce simulation cost and computation time. Fig. 4 illustrates the type of failure mode predicted by the FE modelling and subsequently observed in the test.

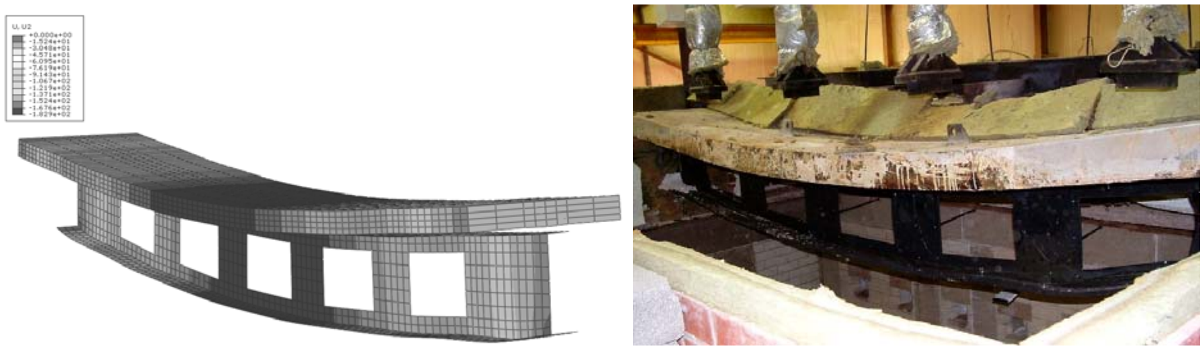


Figure 4: Beam behaviour in FE and test

5.   COMPARISON OF RESULTS

The results obtained from the finite element simulation are compared with those measured experimentally. Fig. 4 demonstrates that the structural behaviour of the composite perforated sections observed from the experiment is in good agreement with the finite element results in terms both of failure modes and overall behaviour. In Fig. 5, the vertical mid-span deflection of the composite beam is plotted against measured bottom-flange temperatures. The simplified analytical model shows good, though slightly conservative, agreement with both the FEA model and the furnace test in terms of limiting temperature.

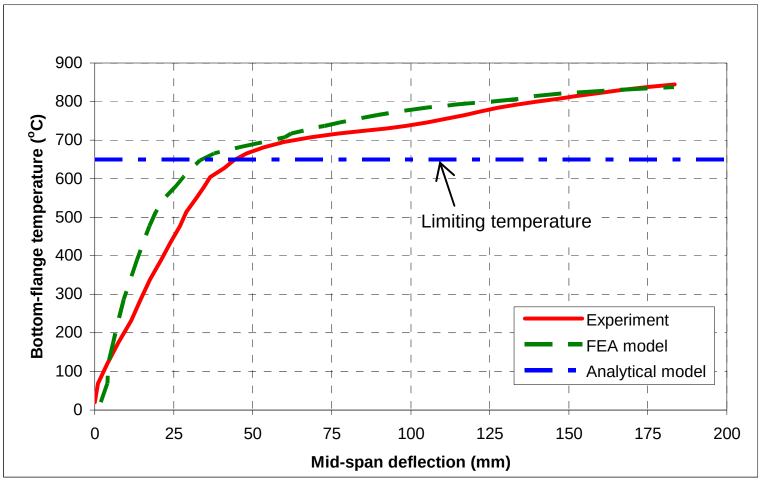


Figure 5: Furnace temperatures and mid-span deflection against time

In addition Fig. 6 clearly shows Vierendeel action developed in the regions of the openings in both the FE model and the experiment. This confirms the analytically predicted failure mode of the perforated section.

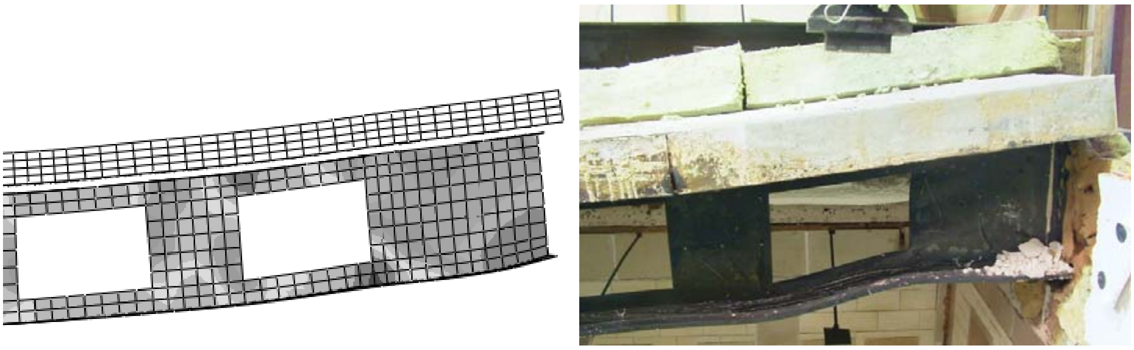


Figure 6: Vierendeel bending failure in FE and test

6. CONCLUSION

The simplified model is clearly able to predict the Vierendeel failure mechanism with reasonable accuracy in terms of the appropriate limiting temperature. It will be necessary, however, to study further the effect of partial shear connection on the composite model subjected to fire, and the contribution of concrete to the shear resistance.

Acknowledgment

The authors gratefully acknowledge support from the Engineering and Physical Sciences Research Council of Great Britain under Grant EP/F001711/1, and International Paint Ltd.

7. REFERENCES

[1] Lawson, R.M.: Design for openings in the webs of composite beams, SCI/CIRIA publication P068, 1987.

[2] Ward, J.K.: Design for composite and non-composite cellular beams, SCI publication P100, 1999

[3] Chung, K.F. and Lawson, R.M.: Simplified design of composite beams with large web openings to Eurocode 4, *Journal of Constructional Steel Research*, Vol. 59, pp. 135-163 (2001).

[4] Liu, T.C.H., Chung, K.F.: Steel beams with large web openings of various shapes and sizes: finite element investigation, *Journal of Constructional Steel Research*, Vol. 59, pp. 1159-1176 (2003).

[5] Chung, K.F., Liu, T.C.H. and Ko, A.C.H.: Steel beams with large web openings of various shapes and sizes: an empirical design method using a generalised moment-shear interaction curve, *Journal of Constructional Steel Research*, Vol. 59, pp. 1177-1200 (2003).

[6] Lawson, R.M., Lim, J., Hicks, S.J. and Simms, W.I.: Design of composite asymmetric cellular beams and beams with web openings, *Journal of Constructional Steel Research*, Vol. 62**,** pp.614-629 (2006).

[7] Steel Construction Institute: Guidance on the use of intumescent coatings for the fire protection of beams with web openings, Publication RT1085 Version 04, 2007.

[8] CEN, Brussels, BS EN 1994-1-2: 2005: Eurocode 4: Design of composite steel and concrete structures. Part 1-2: General rules – Structural fire design, 2005.

[9] Pawtucket, R.I.: ABAQUS user's manual version 6.2, Hibbitt, Karlsson and Sorensen Inc. 2001.

[10] Wong, V.Y.B., Burgees, I.W., Plank, R.J.: Behaviour of Composite cellular steel - concrete beams at elevated temperatures, *International Journal of Steel Structures*, Vol. 9**,** pp.1-15 (2009).