SDSS'Rio 2010 STABILITY AND DUCTILITY OF STEEL STRUCTURES
E. Batista, P. Vellasco, L. de Lima (Eds.)
Rio de Janeiro, Brazil, September 8 - 10, 2010

# BEHAVIOUR OF COMPOSITE FLOOR BEAM WITH WEB OPENINGS AT HIGH TEMPERATURES

**V.Y. Bernice Wong*, Ian W. Burgess* and Roger J. Plank****

* Department of Civil and Structural Engineering, The University of Sheffield, Sheffield S1 3JD, UK
e-mails: v.wong@sheffield.ac.uk, ian.burgess@ sheffield.ac.uk

** School of Architectural Studies, The University of Sheffield, Sheffield S10 2TN, UK
e-mail: r.j.plank@ sheffield.ac.uk

**Keywords**: Composite Beam, Web Opening, Finite Element Modelling, Structural Fire Engineering

***Abstract.*** *A simplified analytical model for composite cellular floor beam, based on currently available design methods, has been completed. This has been used in an initial study of loaded composite cellular floor beams at normal and elevated temperatures. The approach predicts the capacity and failure type of a composite member by applying design criteria for each of the different possible failure modes at successive cross-sections of the member. A finite element investigation into the behaviour, including local instabilities, of cellular composite members subjected to elevated temperatures has also been conducted, considering material and geometrical non-linearities. These studies have been validated by modelling recent full-scale furnace tests on composite cellular beams. Close comparisons are observed between finite element, experimental results and the predictions of the simplified analytical model.*

## 1 INTRODUCTION

Composite cellular floor beams are currently widely used in multi-storey building construction, especially to achieve long spans at the same time as providing passage for service ducts, hence reducing overall building height. The downstand composite beams make use of their full structural depth, maximising the lever arm between the compressed concrete flange and the steel section which acts essentially in tension. The optimisation of this structural form, however, raises questions about potential failure modes, particularly at elevated temperatures.

In practice, web-openings in a beam result in unusual stress distributions within the web, and unique beam failure modes. A web opening produces an additional local ("Vierendeel") bending across the opening due to high shear forces acting on the beam. This can result in the formation of four plastic hinges at the "corners" of the opening. Equally, the shear forces transferred across the web-posts between openings can result in local buckling of these web-posts. The loss of strength and stiffness of structural steel in the fire situation depends on its temperature; the elastic modulus of steel reduces rapidly in comparison to its strength, which results in more rapid reduction of capacities based on buckling than those based on strength. Hence the buckling capacity of web-posts reduces more rapidly with temperature than those based on other failure types. Therefore web-post buckling tends in general to be the critical mode of failure in fire, even for beams with low web slenderness ($d/t$) ratios.

In this paper, a simplified analytical model representing composite cellular floor beam in case of fire is described. This has been used in an initial study of loaded composite cellular floor beams at normal and elevated temperatures. A finite element model taking into consideration the material and geometrical non-linearities has also been developed to investigate the behaviour of cellular composite members subjected to elevated temperatures. These studies have been validated by modelling recent full-scale furnace tests on composite cellular beams.

## 2 ANALYTICAL MODEL

Based on the available design guides [1] - [6] for ambient temperatures, an analytically-based model has been developed for determining the critical temperatures of composite cellular floor beams in fire, taking into account shear force transfer by Vierendeel action across the openings and the forces generated in web-posts. The high-temperature limiting cases of the composite beam are assessed by applying the material properties appropriate to elevated temperature to the ambient-temperature equations.

### 2.1 Resistance to Vierendeel bending

Transfer of shear across a web opening results in the eventual formation of plastic hinges at the four "corners" of the opening, which are assumed to be sited at the corners of the inscribed square in the case of a circular opening. For a composite beam, the composite action developed between the top-tee section and the concrete slab increases the resistance to Vierendeel bending at one of these hinges.

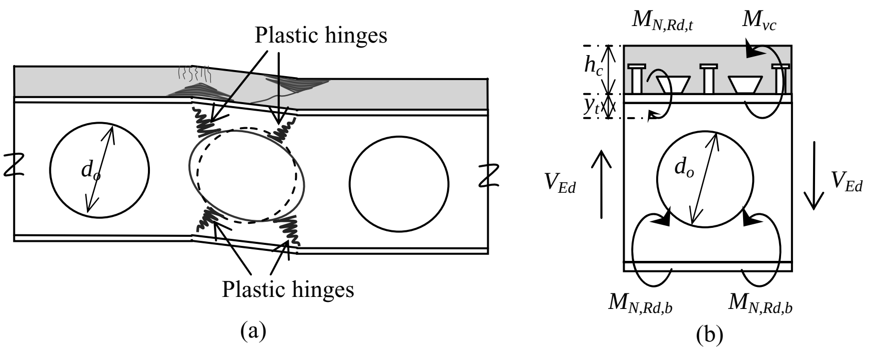



Figure 1: Vierendeel mechanism (a) Mode of failure; (b) Vierendeel bending around web opening.

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

$$M_{v,Rd,fi} = M_{N,Rd,t,fi} + 2M_{N,Rd,b,fi} + M_{vc,fi} \tag{1}$$

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

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

where:

$M_{Rd,fi}$ is the local bending resistance of the tee section. 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 global moment action

$N_{Rd,fi}$ is the resistance of the tee sections

$M_{vc,fi}$ is the bending resistance due to local composite action between the top-tee section and the concrete slab. This may be approximated by:

$$M_{vc,fi} = n_s P_{Rd,fi}(h_c - \frac{x_c}{2} + y_t) \tag{3}$$

where:

$n_s$ 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 of the flange

The applied Vierendeel moment for a circular web opening is calculated by $V_{ED}(0.5d_o)$; where $V_{Ed}$ is the design shear force at a distance $x$ from the support acting over an effective length of $0.5d_o$, where $d_o$ is the diameter of the circular opening.

**2.2 Web-post buckling resistance**

For cellular beams with narrow web-posts between closely spaced openings web-post buckling is often critical, and therefore it is necessary to select an opening size with a suitable web-post width. The SCI guidance [7] - [8] recommends that the web-post width for beams with circular web openings should not be less than 130mm or $0.3d_o$, whichever is the greater. In cellular beam design, each web-post is checked for resistance to local buckling as an equivalent 'strut', by considering a compression force acting over its minimum width $S_o$ (Figure 2).

At high temperature, the shear resistance of the web reduces at a faster rate than bending resistance of the beam, and thus the web is more influenced by local buckling. In fire, the capacity of a web-post ($V_{h,buck,fi}$) is defined as:

$$V_{h,buck,fi} = \chi_{fi} f_{y,fi} S_o t_w \tag{4}$$

where:

$f_{y,fi}$ is the design yield strength of the perforated section at high temperature
$t_w$ is the thickness of the web-post

The value of $\chi_{fi}$ is calculated following the principles of EN1993-1-2 [9], and is defined as:

$$\chi_{fi} = \frac{1}{\phi_{fi} + \sqrt{\phi_{fi}^2 - \bar{\lambda}_{fi}^2}} \quad \text{but } \chi_{fi} \le 1.0 \tag{5}$$

with

$$\phi_{fi} = 0.5[1 + \alpha(\bar{\lambda}_{fi} - 0.2) + \bar{\lambda}_{fi}^2] \tag{6}$$

and

$$\bar{\lambda}_{fi} = \sqrt{\frac{f_{y,fi}}{f_{E,fi}}} \tag{7}$$

The imperfection factor $\alpha$ is taken as 0.49 for $d/t \le 85$ and 0.76 for $d/t > 85$.

The buckling stress ($f_{E,fi}$) acting across the web-post and the slenderness ($\lambda_{fi}$) of the web-post are defined as:

$$f_{E,fi} = \frac{\pi^2 E_{fi}}{\lambda_{fi}^{\;2}} \tag{8}$$

$$\lambda_{fi} = \frac{\sqrt{12}\, l_{e,fi}}{t_w} \tag{9}$$

in which $l_{e,fi}$ is the web-post's effective length at elevated temperature.

For a circular web opening, $l_{e,fi}$ is given by:

$$l_{e,fi} = 0.9 l_e \quad \text{for } d/t \leq 85 \tag{10}$$

$$l_{e,fi} = 1.2 l_e \quad \text{for } d/t > 85 \tag{11}$$

$l_e$ is the web-post effective length at ambient temperature, which is calculated from:

$$l_e = 0.5\sqrt{S_o^{\;2} + d_o^{\;2}} \tag{12}$$

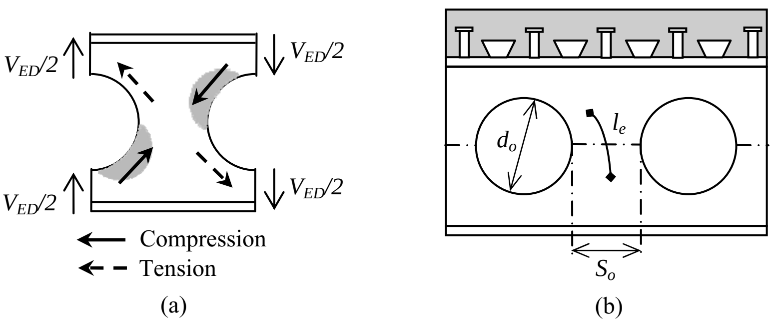



Figure 2: Web-post buckling (a) assumed forces; (b) web-post geometry

The applied vertical compressive force ($V_t$) acting across the web-post is calculated by $V_{ED}/2$; where $V_{Ed}$ is the design shear force at the distance from the support to the centre of the web-post.

## 3 ANALYTICAL MODEL VALIDATION

Results obtained from the proposed analytical model were validated by comparison with available experimental test results and finite element modelling.

### 3.1 Fire tests

*Nadjai et al.* conducted fire tests [10] on composite cellular floor beams heated using an ISO 834 standard fire curve (Figure 3). Table 1, and Figures 4 and 5 summarise the test specimens used.

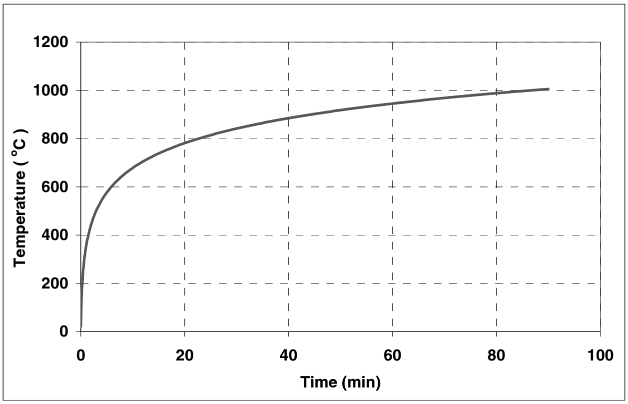



Figure 3: ISO 834 standard temperature-time curve

| Type | Cellular beam (S355) | | | | |
|---|---|---|---|---|---|
| | Beam Size | Opening | Web-post width | Spacing | Applied Load |
| A | Symmetric beam (575x140x39kg/m)<br>Top-tee: UB 406x140x39kg/m<br>Bottom-tee: UB 406x140x39kg/m | 8 x 375mm | 125mm | 500mm | 2 x 54kN |
| B | Asymmetric beam (630x140/152x46kg/m)<br>Top-tee: UB 406x140x39kg/m<br>Bottom-tee: UB 457x152x52kg/m | 6 x 450mm | 180mm | 630mm | 1 x 126kN |
| 150mm thick x 1200mm wide concrete slab of strength 35N/mm$^2$<br>A142 reinforcement mesh of yield strength 460N/mm$^2$<br>Shear connectors of 19mm diameter x 120mm height, equally distributed at 150mm spacing | | | | | |

Table 1: Sectional details of composite cellular beam tests

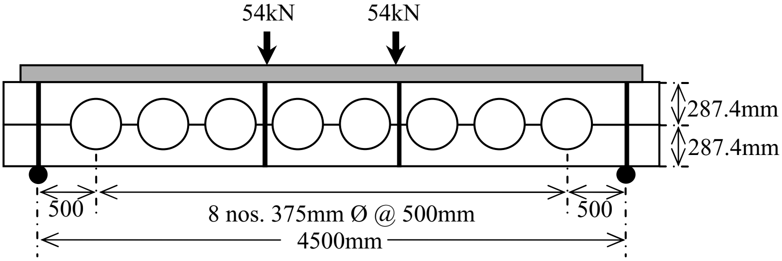



Figure 4: Geometric detail of symmetric composite cellular beam test (Type A)

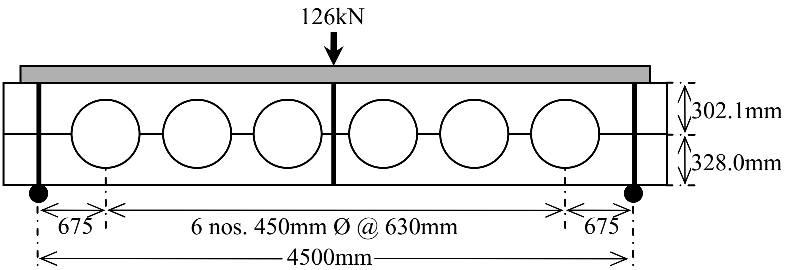
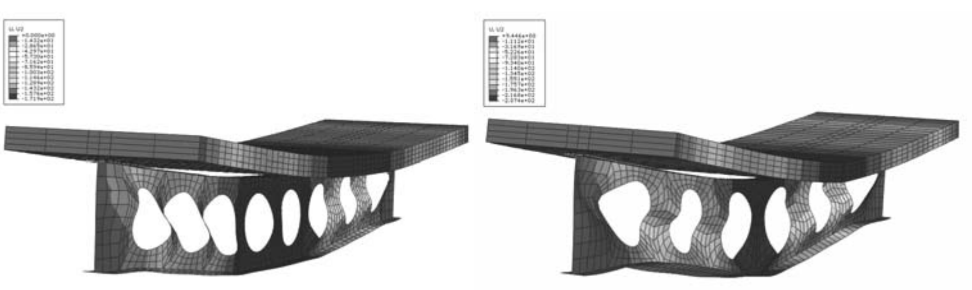



Figure 5: Geometric detail of asymmetric composite cellular beam test (Type B)

**3.2 Finite element (FE) modelling**

The commercial FE package ABAQUS [11] was used to carry out the simulation work. A three-dimensional eight-noded solid element and four-noded quadrilateral shell elements with reduced integration were used to represent the concrete slab and cellular steel beam respectively. Reinforcing mesh in the solid slab element was defined as a layer of steel of equivalent area in each direction. Full interaction between the concrete slab and the steel beam was assumed, due to the high density of shear connectors which was used in the test. Full composite action between the concrete slab and the cellular steel beam was achieved by using a tying constraint to tie their surfaces together. The support and loading conditions in the FE models simulated the experimental conditions, restraining the appropriate degrees of freedom. Figure 5 illustrates the type of failure mode predicted by the FE modelling for beams of Types A and B.



(a) (b)

Figure 5: FE simulation (a) beam Type A web-post buckling; (b) beam Type B web-post buckling

### 3.3 Results and discussion

A summary of the results obtained from the analytical model, FE modelling and experiment are shown in Figures 6 and 7. The structural behaviour of the composite perforated sections observed from the experiments is clearly in good agreement with the finite element results in terms both of failure modes and overall behaviour. Web-post buckling is clearly observed in beams of both Types A and B. Figures 6 and 7 compare between the FE simulation and experiment in terms of the mid-span displacements and the beam bottom-flange temperature. The critical temperatures generated by the proposed analytical model have also been shown. Critical temperatures calculated from the simplified analytical model were 703ºC and 668ºC for beams of Type A and Type B respectively. These are slightly conservative predictions which are appropriate for use in design.

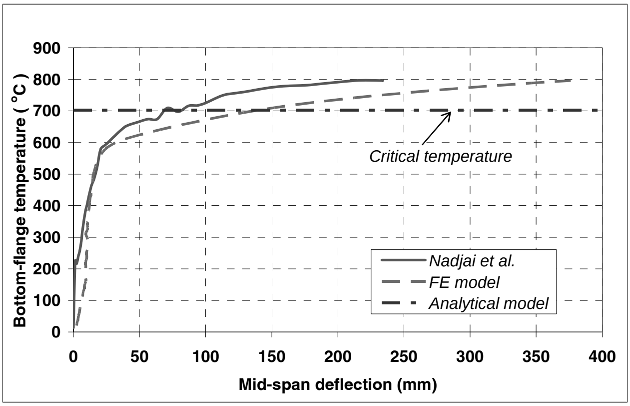



Figure 6: Comparison of mid-span deflection behaviour and critical temperature for Beam Type A

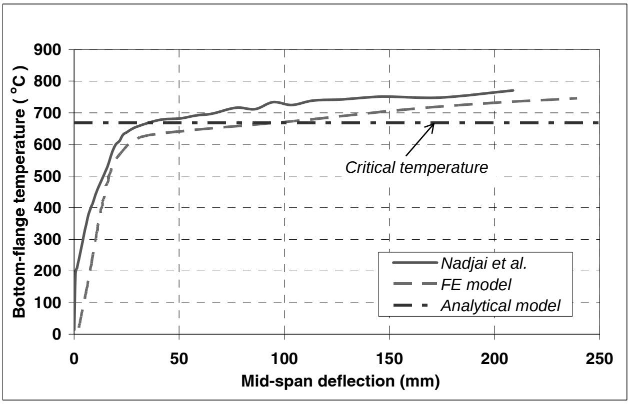



Figure 7: Comparison of mid-span deflection behaviour and critical temperature for Beam Type B

## 4 CONCLUSION

A simplified analytical model for the fire resistance of cellular beams based on available design guides has been presented. This has been validated by comparison with results obtained from available experimental fire tests and finite element modelling. The final failure conditions of the composite cellular beams predicted by the analytical model agree well with the experimental observations and FE simulations. The FE model can be utilised to investigate the high-temperature behaviour of composite cellular beams in far more detail than is possible by testing alone. The use of the proposed simplified analytical model has been shown to have lead to conservative predictions, and to be in reasonable agreement with both the FE and the furnace tests in terms of critical bottom-flange temperatures.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Engineering and Physical Sciences Research Council of the United Kingdom for providing funding for this research work under Grant EP/F001711/1.

## 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*, **59**, pp135-163, 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*, **59**, pp1159-1176, 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*, **59**, pp1177-1200, 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*, **62,** pp614-629, 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] Steel Construction Institute, “Guidance on the fire protection of beams with web openings”, Publication RT1187 Version 01, 2008.

[9] CEN, Brussels, BS EN 1993-1-2: 2005, “Eurocode 3: Design of steel structures. Part 1-2: General rules – Structural fire design”. 2005.

[10] Nadjai, A., Bailey, C.G., Bake, S.M., Ali, F., Talamona, D., Allam, A. “Behaviour of composite floor cellular steel beams at elevated temperatures”. *International Congress on Fire Safety in Tall Buildings, Spain*, pp359-371. 2006

[11] Pawtucket, R.I. “ABAQUS user’s manual version 6.2”, Hibbitt, Karlsson and Sorensen Inc. 2001.