Cover page

Title: Experimental and Analytical Investigations of the Behaviour of Protected Composite Floor Beams with Web Openings in Fire

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ABSTRACT

Intumescent coating is the most common of the passive fire protection options for cellular beams. Applying intumescent coating to cellular beam has generally followed a tabulated method which is only available for beams with circular web openings, and applies geometrical limitations to the positions and sizes of the openings. A full-scale fire test has been conducted recently to investigate the behaviour of an intumescent-protected composite floor beam with rectangular web openings. The loaded test specimen was protected with a specified coating thickness determined on the basis of a multi-temperature assessment, taking into consideration the actual loading condition, as well as the exact position of the web openings. It was observed that the predicted behaviour of the protected beam was in reasonably close agreement with the test result. Observations from the test suggested that the inconsistency of web temperatures along the beam was due to local detachment of the intumescent char from the bottom-flange. The study has been extended to carry out finite element simulations of the fire test, considering material and geometrical non-linearities. The result is directly compared against the experimental results.

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INTRODUCTION

The use of steel beams with regular web openings is becoming more popular in multi-storey building construction, because it is possible to achieve long spans and the system is capable of providing through-passage for service ducts, reducing overall building height. In practice, web-openings in beams result in different stress distributions within the webs from solid-web sections, and these create unique failure modes. In fire, the degradation of strength and stiffness of unprotected structural steel happen at different rates, and this can cause not only early structural collapse but also a change of failure mechanism compared to ambient-temperature performance.

Numerous fire protection technologies are available to protect steel structures. Intumescent coating is the most common of the passive fire protection options for perforated steel beams. This has the advantage of allowing the structural form to remain visible as an architectural feature. In fire, the thin dry film layer foams and expands to 15-30 times its original thickness, developing an insulating char layer.

The current approach provides detailed guidance to determine dry film thicknesses of intumescent coating required for composite beams with web openings. This is generally based on a tabulated method [1], [2], [3], [4] which uses a range of design parameters to estimate limiting bottom flange temperatures, from which the protection requirements of cellular beams may be obtained. These tables only exist for beams with circular web openings, and limit the positions and sizes of the openings. There is clearly a need for rules which incorporate realistic structural behaviour during a fire, considering the actual loading condition and the exact positions of the web openings.

Simulations are presented of a fire test carried out to investigate the behaviour of an intumescent-protected composite floor beam with rectangular web openings.

EXPERIMENTAL INVESTIGATIONS

The fire test involved the heating of a protected composite floor beam with rectangular web openings. The beam's span was 4.2m, with relatively narrow web-posts to induce web-post failure. The beam was an asymmetric composite section with a 200mm x 15mm top-flange, 250mm x 15mm bottom-flange and 6mm x 370mm web. The concrete slab was 130mm thick x 700mm wide, using C25/30 concrete with A142 reinforcing mesh (yield strength 460N/mm^2) and 1.2mm thick Metfloor 55 steel decking. Shear connectors 19mm diameter x 100mm long were used. The nominal and measured yield strengths of the steel beam were 275N/mm^2 and 433N/mm^2 respectively. A total load of 90kN was applied to the top of the concrete slab as four point loads. The beam was tested in a 4m x 3m furnace (Fig. 3) using the ISO 834 standard fire. The target dry film thickness of the specified intumescent was 2.47mm, although its measured average dry film thickness was 2.206mm. The target thickness was determined through a simplified model which takes into account the actual beam loading and the locations of the web openings.

Loads were applied at ambient temperature and maintained during the fire test, which lasted 142 minutes; thermocouples were positioned on the section to record the temperatures throughout the fire test. Figs.1 and 2 illustrate the composite beam geometries and the locations of the thermocouples.

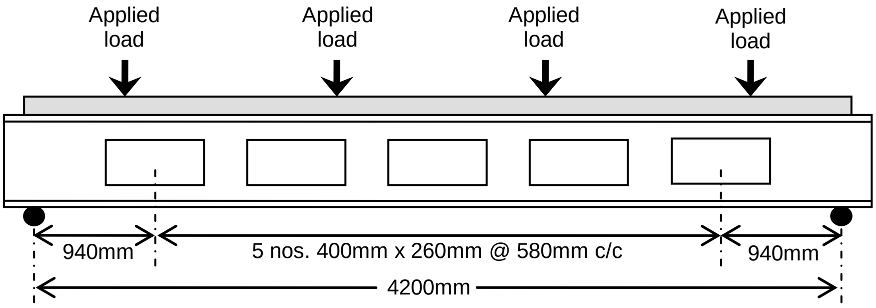


Figure 1. Beam geometries.

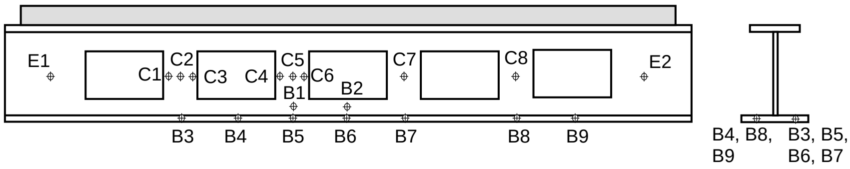


Figure 2. Location of the thermocouples.

Figure 3. Experimental setup: Beam within the furnace, apply loads on beam.

The fire test lasted 142 minutes. It was observed that 20% of Intumescent on the bottom-flange fell off the beam near to a support at 20 minutes (Fig. 4). After 60 minutes, small amounts of Intumescent continued to fall off the bottom-flange.

Fig. 5 shows the recorded temperatures at the centres of the web-posts (positions C2, C5, C7 and C8), averaged end-posts (positions E1 and E2) and the average furnace temperature. Fig. 6 shows the recorded temperatures at the bottom-flange of the beam (positions B4, B6 and B9) below the openings. The higher temperature at B9 is due to the intumescent falling off the bottom-flange of the beam. Comparisons of the measured temperatures at the bottom-flange (positions B3, B5, B7 and B8) measured below the web-posts are shown in Fig. 7. Once again higher temperature at position B8 is caused by the local loss of char

Figure 4. Intumescent on the bottom-flange fell off the beam near the support.

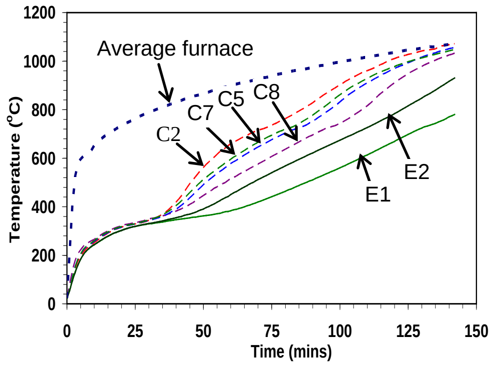


Figure 5. Recorded temperatures at the centre of web-posts, end-posts and average furnace temperature.

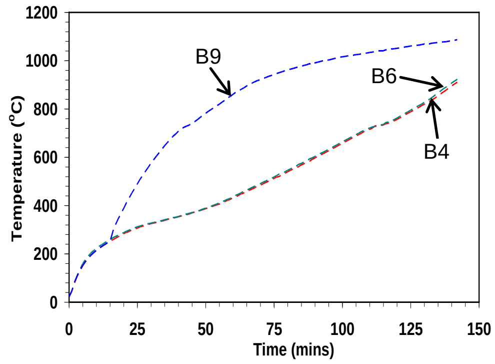


Figure 6. Comparisons of recorded temperatures at bottom-flange measured below bottom-web.

A comparison of the average temperatures at the bottom-flange (positions B3 to B8) against temperatures at the centre of web-posts (position C2, C5, C7 and C8) is shown in Fig. 8. The difference in temperatures between the average bottom-flange and centre of web-post is less than 45°C before 40 minutes. After 50 minutes the web-post was on average 205°C hotter than the bottom-flange. Note that the average temperature at the bottom-flange does not include the temperature at position B9.

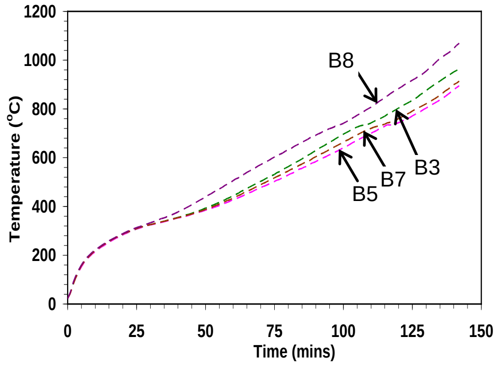


Figure 7. Comparisons of recorded temperatures at bottom-flange measured below web-posts.

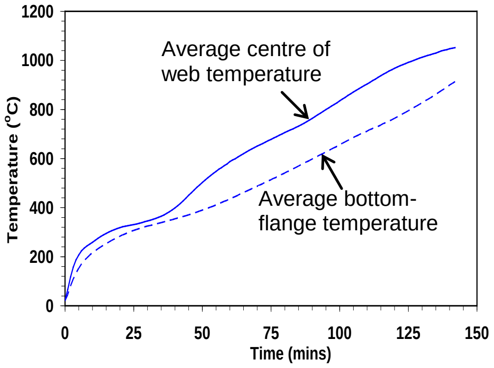
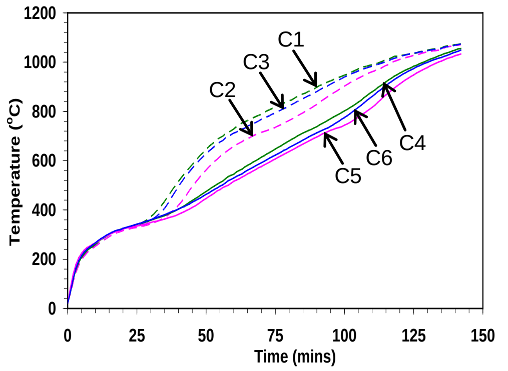
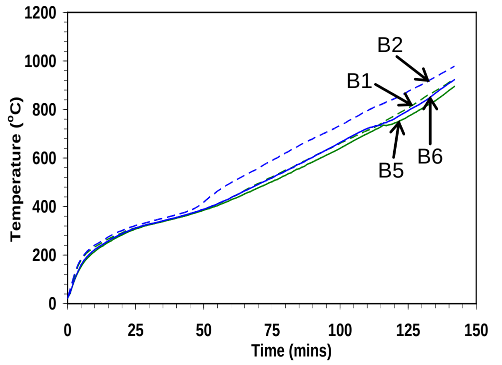


Figure 8. Comparisons of average temperatures at centre of web and bottom-flange.

Fig. 9 compares the recorded temperatures at the first and second web-posts (positions C1–C3 and C4–C6). The temperatures at the three positions on the each web-post remain within 70°C of each other.

Comparison of the recorded temperature at the bottom-flange (positions B5 and B6) against the bottom-web temperatures (positions B1 and B2) is shown in Fig. 10. The temperatures below openings (positions B2 and B6) are hotter than those measured below a web-post (positions B1 and B5). The difference in temperatures between the bottom-web and bottom-flange was about 80°C after 50 minutes.

 Figure 9. Comparisons of recorded temperatures at first and second web-post.	 Figure 10. Comparisons of temperatures at bottom-flange against bottom-web temperatures.

ANALYTICAL INVESTIGATION

The current approach for determining the thickness of intumescent coating required for composite beams with web openings is based on the relationship between web-post temperature and bottom-flange temperature for each protection product. This relates the web-post temperature to the width of the web-post [3] and [4]. Based on the currently available guidance [5], [6], [7] and [8] for composite cellular beam at ambient temperature, an analytical model to predict intumescent thickness for composite beams with web openings has been developed, taking into consideration the actual structural behaviour during a fire. Where web-post buckling is critical, the limiting temperature of the most critical web-post is determined. A limiting bottom-flange temperature is predicted using the web-post factor for the product used.

Assuming that the design of the composite beam with openings is adequate for its overall shear, bending and local Vierendeel resistance requirements, the following simple method is proposed for calculating the resistance of the zone influenced by web-post buckling. In cellular beam design, the resistance of each web-post to local buckling is checked using an 'equivalent strut' principle, by considering the compressive force acting over its width S_o (Fig. 12). At high temperature, the shear resistance of the web reduces at a faster rate than bending resistance of the bottom-flange, 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:

$$V_{h,buck,fi} = \chi_{fi} f_{y,fi} S_o t_w \tag{1}$$

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 buckling stress acting across the web-post ($f_{E,fi}$) is defined as:

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

Slenderness of the web-post (λ_{fi}) for a web with a rectangular opening is:

$$\lambda_{fi} = \frac{3.5d_o}{t_w} \quad \text{for } S_o > d_o \tag{3}$$

$$\lambda_{fi} = \frac{\sqrt{12}l_{e,fi}}{t_w} \quad \text{for } S_o \le d_o \tag{4}$$

in which d_o is the opening depth and $l_{e,fi}$ is web-post effective length at elevated temperature, given by:

$$l_{e,fi} = 0.9l_e \tag{5}$$

l_e is the web-post effective length at ambient temperature, for beam with rectangular web opening, it is calculated from:

$$l_e = 0.7\sqrt{S_o^2 + d_o^2} \tag{6}$$

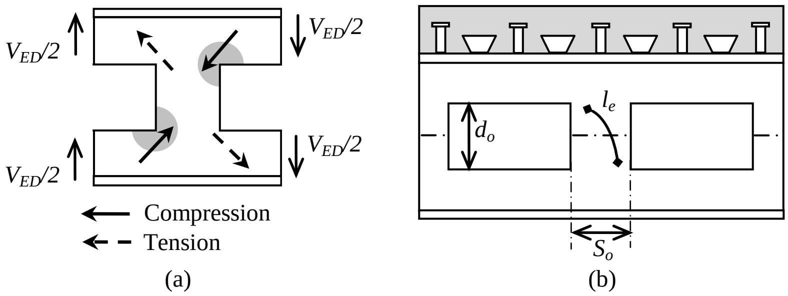


Figure 12. Web-post buckling (a) Mode of Failure; (b) Web-post geometries

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

FINITE ELEMENT (FE) MODELLING

Based on the results obtained from the fire test, geometrically non-linear finite element simulations have been carried out using ABAQUS [9] with non-linear material properties. Three-dimensional 8-noded solid elements and 4-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. Slip between the concrete slab and steel beam is not considered in this analysis; full composite action was achieved by using a tying constraint to tie the surfaces of both components together. The support and loading conditions in the FE models simulated the experimental conditions, restraining the appropriate degrees of freedom. Temperatures of each part of beam section measured in the test were introduced into the finite element models. For the concrete slab, an effective flat slab thickness and an assumed linear distribution of temperature through the thickness were adopted in the FEA models. The measured temperatures at the top and bottom surfaces of the slab were directly applied in the FEA model. The measured yield strength of the steel beam (433N/mm^2) was used in the FEA model. Fig. 13 illustrates the type of failure mode predicted by the FE modelling.

Figure 13. Web-post buckling failure in FE modelling and experimental

RESULTS

A summary of the results obtained from experimental, FE modelling and predicted limiting web temperature are illustrated in Fig. 14. The critical temperatures generated by the proposed analytical model are also shown. The specified intumescent thickness, was expected to provide a fire resistance of 90 minutes, for which the web temperature of the beam needs to be lower than the predicted limiting web temperature. The structural behaviour of the composite perforated sections observed from the experiments was in good agreement with the finite element results in terms both of failure modes and overall behaviour. Web-post buckling was clearly observed in the experiment (Fig. 15). The measured web temperature of the beam at 90 minutes was 25°C higher than the predicted temperature. However, it should be noted that the average measured web temperature is used for comparison, and that this was affected by the inconsistency of web temperatures due to local detachment of the intumescent char from the bottom-flange.

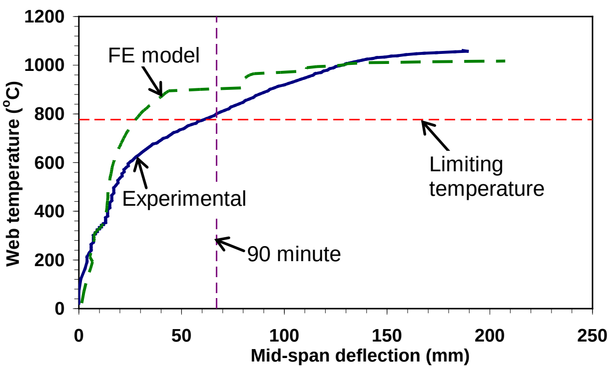


Figure 14. Comparison of mid-span deflection and limiting temperature

Figure 15. Web-post buckling failure mechanism.

CONCLUSION

The final failure conditions of the composite cellular beam predicted by the analytical model agree well with the experimental observations and the FE simulation. All failure modes are accurately predicted by the FE models. The average measured web temperature of the tested beam was 25°C higher than the predicted temperature at the target fire resistance period, although it seems likely that the inconsistency of web temperatures along the beam was due to local detachment of some intumescent char from the bottom-flange.

ACKNOWLEDGEMENTS

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