A detailed investigation on thermal behaviour of slim floor beams with web openings at elevated temperatures

Alam, N., Nadjai, A., Vassart, O., & Hanus, F. (2019). A detailed investigation on thermal behaviour of slim floor beams with web openings at elevated temperatures. *Journal of structural Fire Engineering*, *10*(4), 446-467. https://doi.org/10.1108/JSFE-11-2018-0034

Link to publication record in Ulster University Research Portal

Published in:
Journal of structural Fire Engineering

Publication Status:
Published (in print/issue): 09/12/2019

DOI:
https://doi.org/10.1108/JSFE-11-2018-0034

Document Version
Publisher's PDF, also known as Version of record

General rights
Copyright for the publications made accessible via Ulster University's Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Ulster University's institutional repository that provides access to Ulster's research outputs. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact pure-support@ulster.ac.uk.

Download date: 16/04/2024

The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/2040-2317.htm

Received 2 November 2018
Revised 29 December 2018
19 January 2019
Accepted 7 February 2019

A detailed investigation on thermal behaviour of slim floor beams with web openings at elevated temperatures

Naveed Alam
FireSERT, University of Ulster, Newtownabbey, UK

Ali Nadjai
School Built Environment, University of Ulster, Belfast, UK, and

Olivier Vassart and Francois Hanus
ArcelorMittal, Luxembourg, Luxembourg

Abstract

Purpose – In recent times, the use of steel sections with web openings has become common as slim floor beams because they offer a reduction in weight of the steelwork, accommodate services within the floor depth and provide the composite action. The composite action in these beams is achieved either through the concrete dowels or through concrete plugs. Though these web openings offer several benefits in slim floor beams, they induce the material discontinuity in the steel web, which may affect their shear capacity and/or thermal behaviour. The purpose of this study is to investigate the thermal behaviour of slim floor beams with web openings in fire.

Design/methodology/approach – This research presents findings from experimental and analytical investigations conducted to study the thermal behaviour of slim floor beams with web openings in fire. For this purpose, an experimental investigation was conducted, which shows that the presence of web openings has a major influence on temperature development across the steel section as well as along the span of these beams. The behaviour of the tested slim floor beam is validated using finite element modelling. The validated finite element model is then used to conduct a sensitivity study to analyse the influence of different opening spacings, sizes and shapes on the thermal performance of slim floor beams in fire.

Findings – Test results show that the presence of web openings has a major influence on temperature development across the steel section as well as along the span of these beams. Temperatures on the web below the openings are found to be higher as compared to those recorded on the adjacent solid steel web. It is also observed that temperatures on the steel web above the openings are lesser than those on the adjacent solid steel web. Parametric studies conducted using the verified analytical modelling methods show that different opening spacings, sizes and shapes have a variable impact on the thermal behaviour of slim floor beams in fire. Closely spaced and larger opening sizes were found to have a more severe influence on their thermal behaviour in fire as compared to widely spaced and smaller openings. It was also found that the behaviour of these beams is influenced by the shape of the openings with rectangular openings resulting in more severe thermal distributions as compared to circular openings.

Originality/value – The findings from this research study are highly valuable as they contribute to the existing knowledge database. There is a lack of experimental and analytical investigation on performance of slim floor beams with web openings at elevated temperatures. The results and conclusions from this study will help in developing innovative designs for slim floor beams and will help in reducing the fire related risk associated with structures comprising of slim floor beams with web openings.

Keywords Slim floor beams, Web openings, Thermal response, Fire tests, Finite element modelling

Paper type Research paper

Journal of Structural Fire Engineering
Vol. 10 No. 4, 2019
pp. 446-467
© Emerald Publishing Limited
2040-2317
DOI 10.1108/JSFE-11-2018-0034

1. Introduction

Although the use of composite beams offers longer floor spans, these beams in most cases are deeper in comparison with reinforced concrete beams. This increase in depth is a major disadvantage, especially in tall buildings. The use of slim floor beams in high-rise buildings is advantageous because of their shallower depths resulting from the partial encasement of steel section within the floor (De Nardin and El Debs, 2009). The partial encasement protects the steel sections from direct exposure to heat and fire and improves their fire resistance. The concrete encasement also contributes towards the stiffness of the slim floor beams, enhancing their bending resistance by reducing deflections and vibrations in service conditions.

The use of the slim floor beams aids in reducing the construction cost because they consume lesser building materials. The combination of these beams with the metal decking reduces the construction time and eliminates additional requirements of formwork and scaffolding (Mullet, 1998; Newman, 1995). Slim floor beams also help in assimilating the services within the floor depth through the web openings. Though the web openings offer numerous advantages, they also reduce the vertical shear resistance of these beams. Previous experimental and analytical investigations have shown that the concrete between the flanges of the steel section in these beams contributes towards their shear capacity compensating for the loss of the steel web. In some cases, the encased concrete increases their shear capacity significantly, twice as that offered by the bare steel beam section (Tsavdaridis *et al.*, 2013; Tsavdaridis and D'Mello, 2012). Further, experimental investigations have also been conducted to study the longitudinal shear resistance offered by these beams in terms of the composite action resulting from the concrete dowels or concrete plugs. These investigations have shown that the presence of the concrete dowels and plugs improve the longitudinal shear stress transfer mechanism in these beams (Huo and D'Mello, 2013). Though several investigations are available in literature which address their behaviour at ambient temperatures (Tsavdaridis *et al.*, 2013; Tsavdaridis and D'Mello, 2012; Huo and D'Mello, 2013), their response at elevated temperatures needs to be investigated and addressed.

1.1 Aims and objectives

The work presented herein is an experimental and analytical investigation conducted to study the influence of the web openings on thermal response of slim floor beams in fire. This investigation addresses any influences of material discontinuities and the resulting influences on their thermal behaviour in fire. Data acquired from this test are one of a kind and will help to understand the behaviour of these beam types at elevated temperatures. Analytical investigations on the spacings, sizes and shapes of the web openings will highlight the influence of these parameters on the fire behaviour of slim floor beams and will help with better designs and improved solutions for future use.

1.2 The scope of research

The scope of this study is limited to investigations on thermal behaviour only. During this research program, no investigations are conducted to analyse the influence of the web openings on the structural response of slim floor beams in fire.

2. Experimental programme

2.1 Test specimen and heating conditions

The fire test was conducted on a slim floor beam assembly to analyse any influence of the presence of web openings on the thermal behaviour in fire. As mentioned before, the scope of this study is limited to investigations on thermal behaviour only; hence, no external loads

were applied on the specimen during the test. The tested slim floor beam assembly was 1000 mm wide and 2000 mm long, corresponding to the size of the furnace, which is 2000 mm $\times$2000 mm in the plan. The slim floor beam consisted of a steel section, HEA-220, and a steel plate that is 400 mm wide and 15 mm thick made from grade S355 steel. This steel plate was welded to the bottom flange of the steel beam along its length. The overall depth of steel section was 225 mm, including the welded plate, as shown in Figure 1(c). The composite floor consisted of a steel decking and normal weight concrete with a target strength of 30 N/mm^2 at 28 days. The steel decking used for the floor construction is MD-50, a profiled and galvanised steel floor decking used for the construction of composite floor slabs. The overall depth of the test assembly was 280 mm, including a 55 mm layer of concrete above the top flange and the 15-mm-thick welded steel plate, as shown in Figure 1. Concrete above the top flange was reinforced using A-142 steel mesh with flying ends and with minimum laps of 400 mm. This reinforcing mesh is positioned using 15 mm deep spacers to maintain its position above the top flange. The sides of the slim floor beam

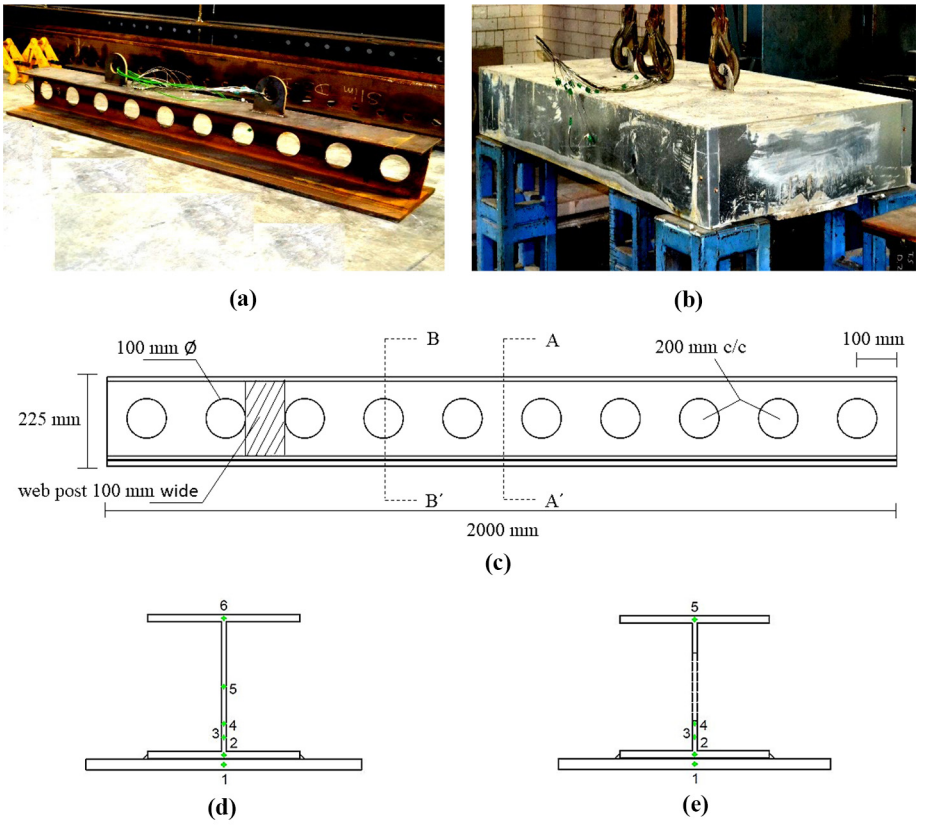


Figure 1.
Details of the test assembly

Notes: (a) Steel beam with web opening; (b) test specimen with composite slab; (c) side elevation of the steel beam; (d) section at AA′; (e) section at BB′

assembly consisted of steel sheets that served as a permanent formwork during construction, as shown in Figure 1(b).

The steel section of the slim floor beam was fabricated with 100 mm diameter web openings with centre-to-centre spacings of 200 mm throughout its length. In total, ten openings were fabricated in the web in such a way that their centres coincided with the centreline of the web, 94 mm from the top and the bottom flange. During the fabrication of the web openings, a solid steel web with a minimum width of 100 mm was produced between the edges of the openings, as shown in Figure 1(a). The first openings at both ends of the steel section were positioned at 100 mm centres from the beam edges, which produced a solid steel web of 50 mm at beam ends. The minimum depth of the solid steel web above and below the edge of openings was 44 mm.

During the fire test, only thermal data were recorded while no arrangements were made to document any vertical or horizontal deformations. Temperatures within the furnace and on the slim floor beam assembly were recorded using type K-310 thermocouples. The furnace temperatures were monitored via five thermocouples to ensure the heating conditions were in accordance with the standard fire, ISO-834. The temperatures on the slim floor beam assembly were monitored through thermocouples positioned on the steel beam at two locations along its span, section AÁ and section BB¨ shown in Figure 1(c). These sections are positioned along the centreline of the openings and in the middle of the solid steel web. The temperatures at section AÁ were monitored using six thermocouples, one each positioned on the middle of the welded steel plate, bottom flange and the top flange while the remaining three were positioned on the steel web. Two of the thermocouples on the steel web were positioned at 20 mm and 40 mm from the inner edge of the bottom flange, while the third one was positioned in the middle of the steel web, as shown in Figure 1(d). The temperatures at the web opening were monitored at section BB¨ using five thermocouples. Three of these thermocouples were positioned in the middle of flanges and welded steel plate. The thermocouples on the web were positioned at 20 mm and 40 mm from the inner edge of the bottom flange, as shown in Figure 1(e). Thermocouple positioning at section AÁ and BB¨ was kept similar except for the one on the middle of the steel web at section AÁ. Such an arrangement of thermocouples was valuable in investigating the influence of the web openings on the thermal behaviour of slim floor beams because they represent the parts of the steel beam at the openings as well as at the solid steel web.

2.2 Test procedure and results

The fire test on the slim floor beam assembly with web openings was conducted at Fire Safety Engineering Research and Technology (FireSERT), Ulster University on the 18 January 2018. The test was conducted using a gas-fired furnace, which lasted for 90 min. The test assembly was placed on top of the furnace which covered the central 1000 mm furnace width while the remaining part of the furnace top was covered using reinforced concrete slabs. The interface between the test assembly and the concrete slabs was filled using ceramic fibre blanket to control the heat and smoke and to allow any vertical deformations of the test beam resulting at higher temperatures. In addition, any openings in the furnace were filled using the fibre blanket to control smoke and heat. As the test was conducted to investigate only the thermal behaviour of slim floor beams, no special support conditions were provided at the ends and the beam assembly rested directly on top of the frame built over the furnace walls. To accommodate any expansion resulting at higher temperatures, no restraints were applied to the ends of the test assembly. All thermocouples were connected to the data logging system where the temperatures were recorded for the whole duration of the fire test. Once the beam assembly was ready for testing, it was heated

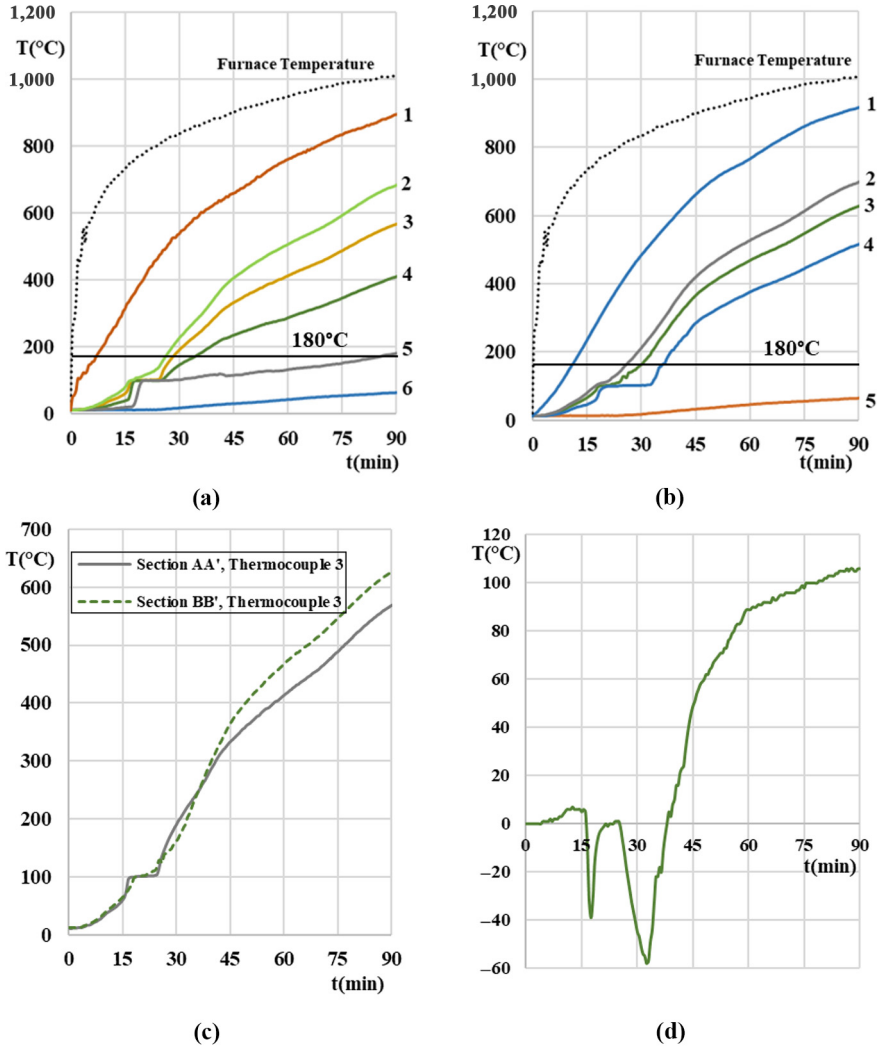
in accordance with the standard fire curve, ISO-834 (International Standards Organization, 1999). The heating of the test assembly continued for a period of 90 min, during which thermal data was recorded. After 90 min of standard fire exposure, the test was stopped, and the data acquisition was discontinued.

Data acquired during the fire test in terms of the temperatures recorded at thermocouple positions at section AÁ and section BB¨ are presented in Figures 2(a) and (b). The numbers corresponding to temperatures in Figure 2 represent the thermocouple positions shown earlier in Figure 1(d) and (e). Similar to the results obtained from the previous investigations on the slim floor beams (Alam *et al.*, 2018a; Maraveas *et al.*, 2016; Alam *et al.*, 2018b), a high thermal gradient across the beam section was observed with the exposed lower parts being at higher temperatures in comparison to the unexposed upper parts. It is also observed that there is a higher temperature difference between the welded steel plate and the bottom flange of the steel beam, as shown in Figures 2(a) and (b). These temperature differences are more than 250°C after 25 min of fire exposure and remain high throughout the duration of the fire test similar to the results in a previous investigation by the authors (Alam *et al.*, 2018c). The recorded temperatures on the top flange remain below 180°C throughout the duration of the fire test; hence, the insulation criteria are satisfied. These criteria have been defined in BS 476 part 20 section 10.4 (British Standards Institution, 1987). It states that the temperature on the unexposed surface should not exceed 140°C on an average and 180°C at any position. As the fire test was conducted to investigate the influence of the web openings on thermal behaviour of slim floor beams in fire, the temperatures recorded at thermocouple position 3 at section AÁ and BB¨ are presented in Figure 2(c). It is seen that the temperatures recorded on the steel web under the opening are higher compared to those recorded on the solid steel web at same thermocouple positions. These temperature differences are presented in Figure 2(d), which shows a temperature difference of 90°C and 107°C after a fire exposure of 60 min and 90 min, respectively. The resulting temperature difference is because of the discontinuity of the steel in the web. During the pouring of concrete, the steel in the web opening is replaced by the concrete that has a lower thermal conductivity. This concrete restricts the efficient flow of heat across the beam section when exposed to fire. As a result, the temperatures on the web under the openings are higher in comparison to those on the adjacent solid steel web. The recorded test data shows that the presence of the web openings in slim floor beams has a considerable influence on their thermal behaviour in fire. It is interesting to note that a phase delay exists for around 10 min once the temperature at thermocouple position 3 reaches 100°C. This is because the migration of moisture, which consumes the heat.

3. Analytical modelling

3.1 Methodology

Finite element modelling for the test assembly was performed using ABAQUS (ABAQUS, 2016). Though several analytical investigations are available on the behaviour of shallow floor systems in fire, these previous studies address the slim floor beams without web openings (Alam *et al.*, 2018a; Maraveas *et al.*, 2012). The current study is the first of the analytical investigations addressing the behaviour of slim floor beams with web openings at elevated temperatures. The proposed analytical method is first validated by replicating the data acquired during the fire test. To make the analysis economical in terms of time, a quarter of the test assembly is modelled during the validation process. The beam assembly is heated using the recorded furnace temperatures during the analytical modelling. The boundary conditions of the beam assembly are kept similar to those used during the test. Non-linear material properties, including the thermal conductivity, specific heat, and the density are taken from the Eurocodes, EN 1994-1-2 (European Committee for Standardization, 2014). The steel and



Notes: (a) Recorded temperatures at Section AA′; (b) recorded temperatures at Section BB′; (c) temperatures at section AA′ and BB′ for thermocouple position 3; (d) temperatures difference for thermocouple position 3 at section AA′ and BB

Figure 2.
Figure showing the test data

concrete parts of the assembly are modelled using eight-node hexahedral solid linear heat transfer elements (DC3D8), commonly used for such analytical investigations. Heat transfer through the surfaces of the test assembly is modelled via convection and radiation. The convection coefficients for exposed and unexposed surfaces are taken as 25 and 9 W/m^2K, respectively, following the Eurocode (EN 1992-1-2) recommendations (European Committee for Standardization, 2008). Any heat transfer through radiation from the unexposed surfaces is ignored while the same for the exposed surfaces and for the cavity between the welded plate

and bottom flange is modelled using an emissivity of 0.7 following the recommendation of the Eurocodes (EN 1993-1-2 and EN 1991-1-2), (European Committee for Standardization, 2009a; European Committee for Standardization, 2009b). Perfect thermal contact is modelled between the steel and the concrete, which allows efficient and full heat transfer between these materials. Similar thermal contacts for these material types have previously been modelled during analytical investigations conducted on shallow floor systems (Alam *et al.*, 2018a; Maraveas *et al.*, 2012).

3.2 Results

Results obtained from the analytical modelling of the slim floor beam assembly are presented in Figure 3. The thermal contours in Figure 3 show the influence of web openings on the heat transfer across the section as well as along the span of the slim floor beam. The thermal contours for the beam are presented at the beginning of the analysis before fire exposure and at time intervals of 15, 30, 45, 60 and 90 min of fire exposure. Similar to the fire test, temperatures predicted on the web below the opening are higher compared to those predicted on the adjacent thermocouple positions on the solid steel web. The thermal contours show that the temperatures on the web above the openings are lesser than those predicted on the adjacent solid steel web at the same positions. The thermal gradient in the analytical model is significant for the slim floor beam throughout or during the fire exposure

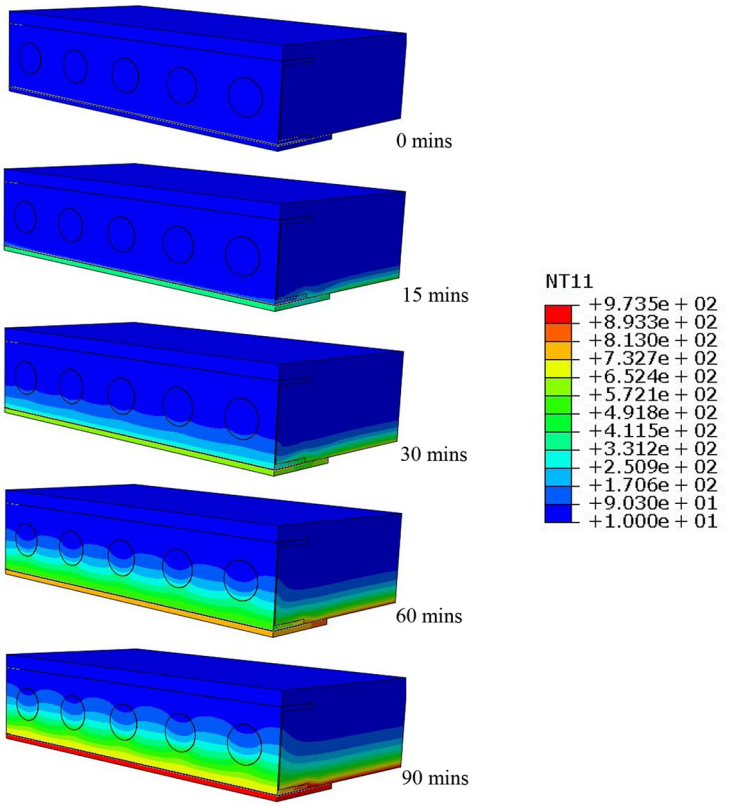


Figure 3.
Analytical results showing thermal contours at different time intervals of ire exposure

because of the concrete encasement. It is seen that with the increase in the fire exposure time, the temperatures predicted on the solid steel web are higher compared to those predicted in the adjacent concrete in the web opening. Similarly, the thermal contours show that the predicted temperatures on the part of the web above the web openings are much lesser than those predicted on the adjacent solid steel web. The maximum temperatures are predicted on the welded steel plate where the recorded temperatures are 973.5°C after 90 min of heating. The temperature difference between the welded steel plate and the bottom flange was also predicted to be high. The top flange of the slim floor beam is much cooler than the bottom part of steel beam and the predicted temperatures after 90 min of fire exposure remain below 100°C for this part.

Thermal predictions obtained from the analytical modelling are presented and compared with the recorded test data for different thermocouple positions in Figure 4. The numbers corresponding to the thermal data in Figure 4 are the thermocouple positions, which represent their positions on the steel beam at section AÁ and section BB¨, as shown earlier in in Figures 1(d) and 1(e). As seen in Figure 4(a), the thermal predictions from the analysis are in close agreement with the recorded test data for all thermocouple positions at section AÁ. The dashed lines in Figure 1(a) represent the thermal predictions from the analytical modelling, while the solid lines represent the recorded test data at the same location. Similarly, the thermal predictions obtained for all five thermocouple positions at section BB¨ are in very good agreement with the test data, as shown in Figure 4(b).

It is seen that the thermal predictions from the analytical modelling are in very good agreement with the test data for thermocouple positions at the solid steel web as well as for the part of the slim floor beam section where the steel web is discontinuous because of the presence of openings. These results show that the analytical modelling method used in this study can predict the thermal response of slim floor beams with web openings with good accuracy. Hence, the analytical method can be used to conduct sensitivity studies to investigate the influence of different parameters related to web openings on the thermal behaviour of slim floor beams at elevated temperatures.

4. Sensitivity studies

A sensitivity analysis was conducted to analyse the influence of the spacing, size and shape of the web openings on thermal behaviour of slim floor beams at elevated temperatures. During this part of the research, the verified analytical modelling method detailed in Section 3 was used and one-fourth of the test assembly was modelled. The ambient temperature during the analytical investigations was set at 20°C in all cases. The influence of different opening spacings, sizes and shapes is investigated in terms of predicted temperatures on the steel web below and above the openings and those predicted on the solid steel web at similar thermocouple positions. Furthermore, the predicted temperatures on the parts of the steel web influenced by the design modifications resulting from the variations in the spacings, sizes and shapes of the openings are also provided.

4.1 Sensitivity studies on centre-to-centre spacing of openings

To investigate the influence of the centre-to-centre spacings of the openings, four slim floor beams with variable opening spacings were modelled and analysed. The shape and size of the openings and their position along the vertical axis of the beam was kept same in all cases. The circular openings were 100 mm in diameter and were positioned at 44 mm from the inner edges of the top and the bottom flanges. Four cases of the opening spacings were investigated where the centre-to-centre spacings were kept 150 , 200 , 300 and 600 mm, as

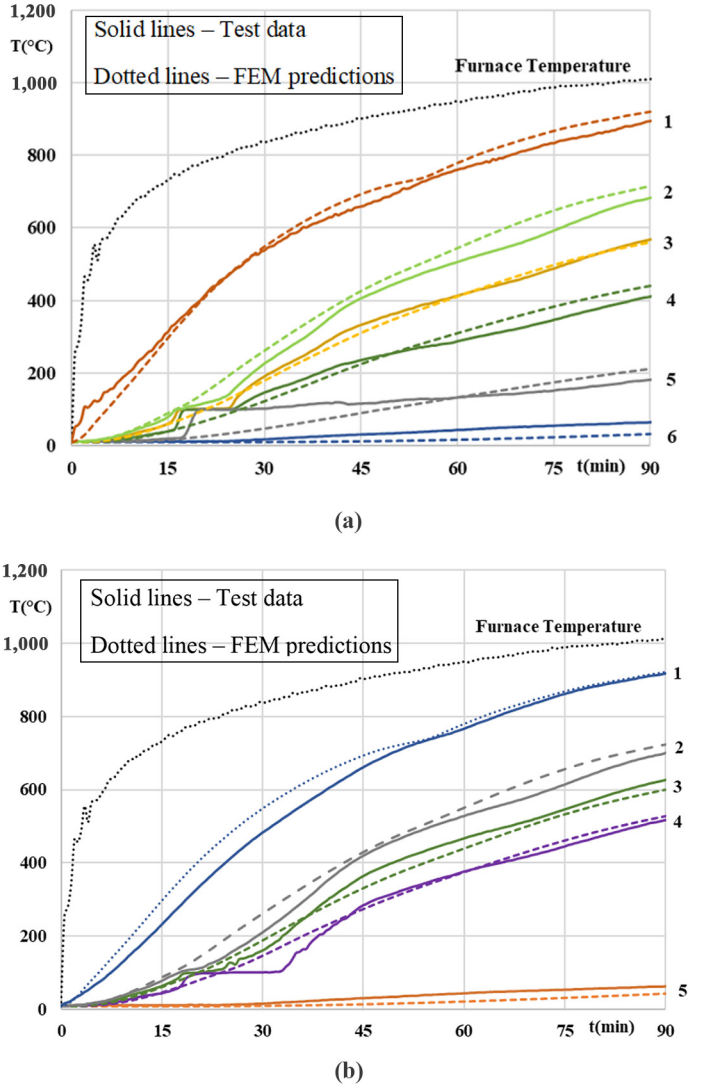
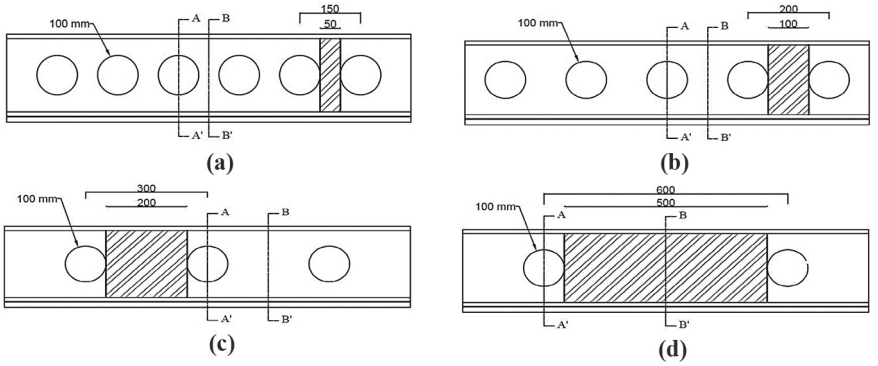


Figure 4.
Comparison of test data and analytical modelling predictions

Notes: (a) Section AA´; (b) section BB´

shown in Figure 5. The variations in the opening spacings results in different widths of the solid steel web between the openings. For the slim floor beam assembly with 150 mm opening spacings, the minimum width of the solid web was 50 mm, while for the ones with 200, 300 and 600 mm opening spacings, the minimum width of the solid steel web was 100, 200 and 500 mm, respectively. These variations in the geometry of the slim floor beams are presented in Figure 5. With the exception of the variations in the opening spacings, the slim floor beam used during this part of the study is similar to the slim floor beam used during



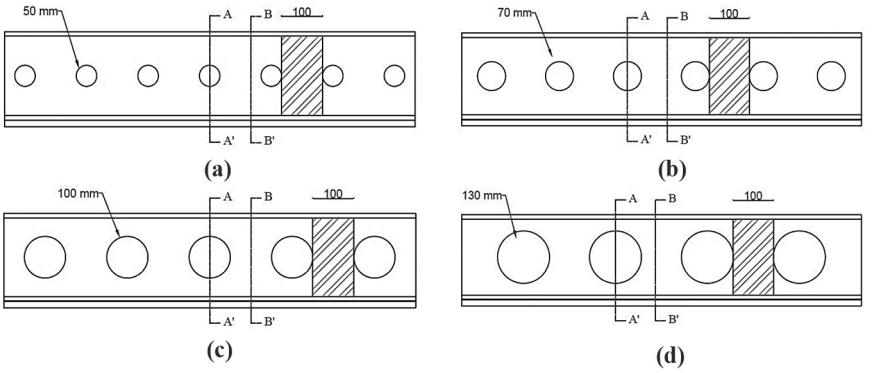
Notes: (a) At 150 mm centres; (b) at 200 mm centres; (c) at 300 mm centres; (d) at 600 mm centres

Figure 5. Slim floor beam assemblies with 100 mm diameter openings and different spacings

the experimental investigation and the one used during the analytical modelling presented earlier in Section 3.

4.2 Sensitivity studies on the size of openings

The size of the web openings for slim floor beams has been found to vary from one beam to another depending upon the design and utility requirements. No restriction on the minimum size of the web openings is available in literature while the maximum allowable size of these openings is recommended not to exceed 70 per cent of the web depth (Huo and D'Mello, 2013). Being mindful of the various possibilities for sizes of the web openings, a sensitivity study was conducted to investigate the influence of 50, 70, 100 and 130 mm web opening sizes on thermal response of slim floor beams in fire. The minimum width of the solid steel web between the openings was kept same and equal to 100 mm in all four cases as shown in Figure 6. The maximum size of the openings selected during this study, 130 mm, represents the openings with approximately 70 per cent of the web depth. The investigated slim floor



Notes: (a) 50 mm diameter openings; (b) 70 mm diameter openings; (c) 100 mm diameter openings; (d) 130 mm diameter openings

Figure 6. Slim floor beams with 100 mm solid steel width and different opening sizes

beam assembly was again similar to the test specimen and the beam assembly used for analytical investigations described earlier in Section 3.

4.3 Sensitivity studies on the shape of openings

During the experimental programme and during the analytical investigations conducted in the above sections, only circular-shaped web openings with different sizes and spacings have been investigated. Though the use of circular web openings is common, various other shapes of web openings may also be encountered during construction work. Among other opening shapes, squared openings, elongated openings and rectangular openings are often used in the construction. In this part of the study, investigations are conducted on slim floor beam assemblies with circular, elongated, squared and rectangular web openings such that the minimum width of the solid steel web as well as the depth of the steel web above and below the openings is kept constant in all cases. The investigated slim floor beam cases with different opening shapes are shown in Figure 7. The circular openings investigated are 100 mm in diameter while the square openings are 100 mm in each direction. The elongated openings have a maximum length of 300 mm, including a semi-circle of 100 mm diameter at each end. Similar to the elongated opening, the rectangular openings are 300 mm long. The depth of the elongated and the rectangular openings is 100 mm, similar to the depth of the square and circular openings. The details of the investigated cases are presented in Figure 7, which shows the minimum width of the solid steel web between the openings in all cases was 100 mm. The depth of the steel web above and below the openings was also equal for all cases with the edge of the openings being at 44 mm from the inner edges of the top and the bottom flanges.

5. Results from sensitivity studies

Results obtained from the sensitivity analysis are presented here for different slim floor beam cases. As mentioned in the proceeding sections, sensitivity investigations were conducted to analyse the influence of the opening spacings, sizes and shapes on the thermal behaviour of slim floor beams. The results presented herein highlight the influences resulting from these design variations. The results obtained for each part of the sensitivity investigation are presented in the following sections;

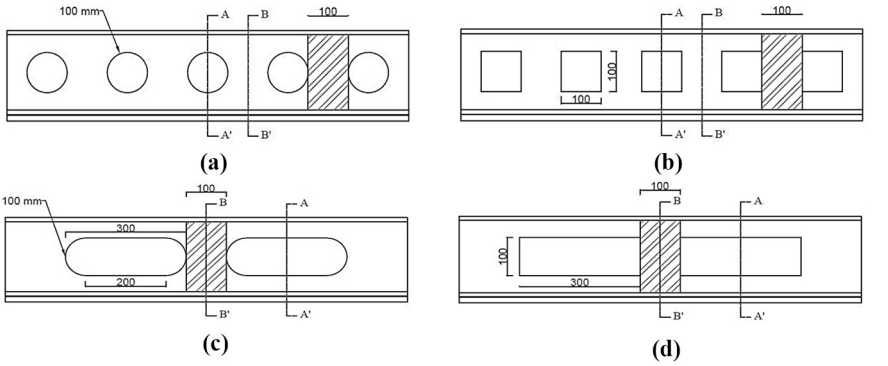


Figure 7.
Slim floor beam assemblies with 100 mm solid steel width and with different opening shapes

Notes: (a) 100 mm diameter circular openings; (b) 100 mm square openings; (c) 300 mm elongated openings; (d) 300 mm rectangular openings

5.1 Sensitivity studies on centre-to-centre spacing of openings

The influence of the variation in the centre-to-centre spacing of the openings on the thermal behaviour of slim floor beams are presented in terms of temperatures predicted on the steel web. The results from the analysis are presented in terms of the temperatures predicted for thermocouple positions above and below the centreline of the web openings and those predicted on the adjacent solid steel web at similar thermocouple positions. Because the size of the web openings was kept 100 mm in diameter in all cases; hence, the centre-to-centre spacing between these openings changed the width of the solid steel web from one case to another. The thermal contours obtained from the analytical modelling after a period of 120 min of standard fire exposure for all four cases are presented in Figure 8. It is seen that the thermal contours on the slim floor beam in each case are different. This shows that the variations in the opening spacings have an influence on the thermal behaviour of slim floor beams in fire. The fire test was conducted for 90 min; hence, the model verification presented earlier is presented for 90 min. However, the sensitivity study was conducted for an additional 30 min; thus, the results for the sensitivity study are presented for an extended duration of 120 min.

During the experimental investigation it was found that a major temperature difference exists on the steel web at openings and on the adjacent solid part while the other parts of the

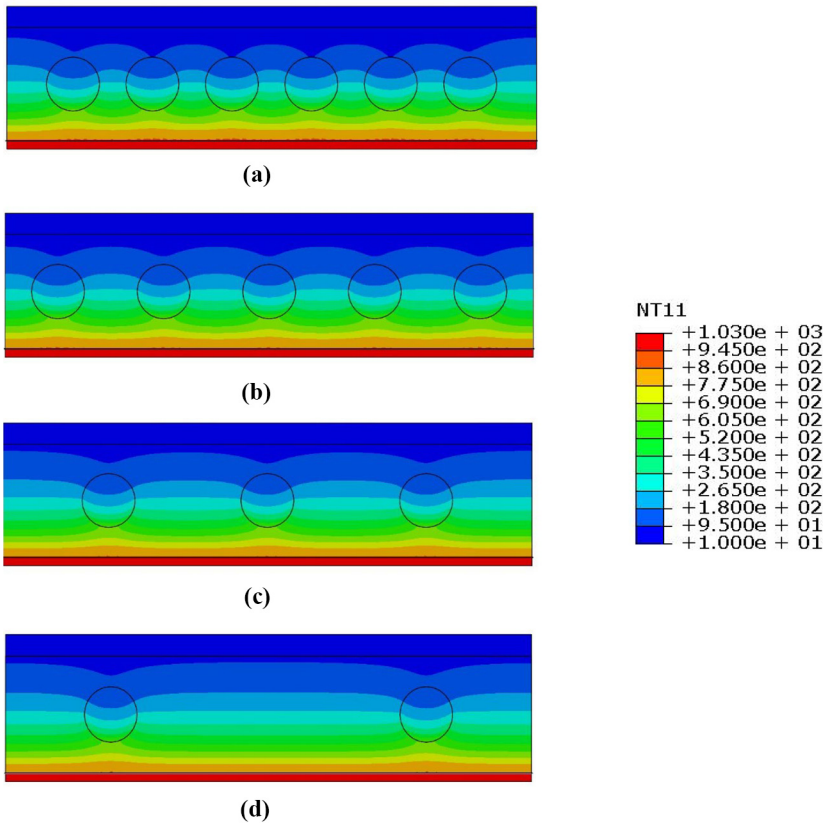


Figure 8. Analytical results showing the thermal contours and the influence of centre-to-centre spacings of web openings for (a) 150 mm centres; (b) 200 mm centres; (c) 300 mm centres; (d) 600 mm centres

beam, including the bottom flange, the welded steel plate and the top flange, were not highly affected. To analyse the influence of the opening spacings, respective temperature differences predicted during the analysis for the thermocouple positions 3 and 5 (shown earlier in Figure 1) at section AÁ and BB¨ are presented in Figures 9(a) and 9(b), respectively. It is seen that for smaller centre-to-centre spacing of openings, temperature differences between the web below the opening and on the adjacent solid steel web are smaller compared to those predicted for larger opening spacings. Similarly, temperatures differences predicted on the steel web above the web openings and on the adjacent solid steel web at thermocouple position 5 are lesser for

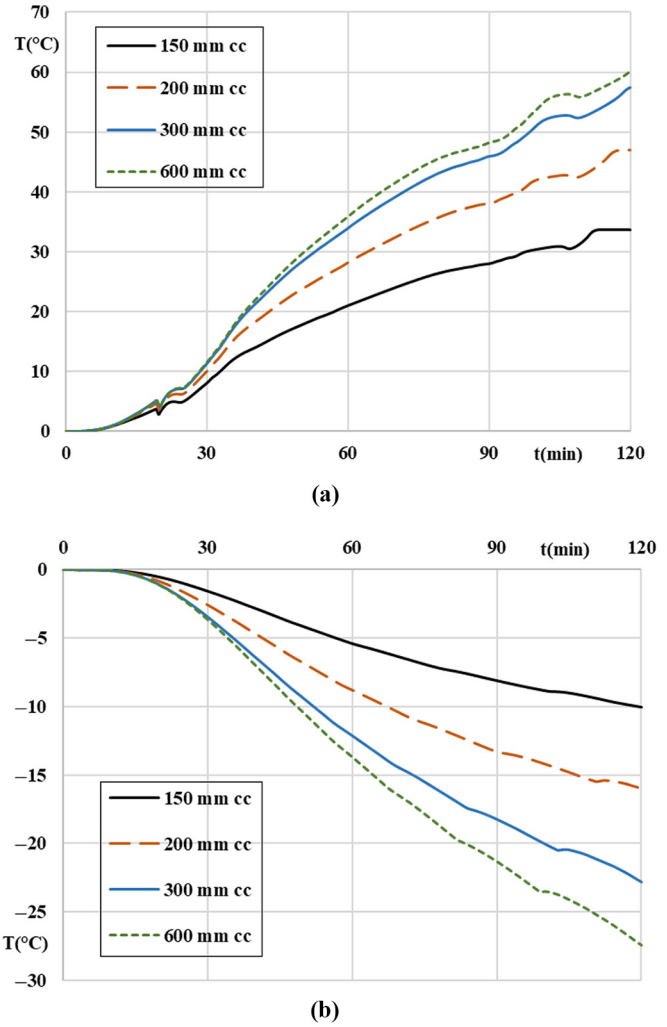


Figure 9.
Temperatures differences on the steel web at openings and on the adjacent solid steel web for different spacings of web openings

Notes: (a) For thermocouple positions 3; (b) for thermocouple positions 5

smaller opening spacings compared to those predicted for larger opening spacings. Nevertheless, in all cases, temperatures recorded on the web below the openings are higher in comparison to those predicted on the adjacent solid steel web. The predicted temperatures are lesser on the steel web above the opening in comparison to those predicted on the adjacent solid steel web.

Temperatures predicted at the thermocouple position 3 below the web openings for all cases were found be similar irrespective of the centre-to-centre spacings of the openings. However, a difference in the predicted temperatures on the solid steel web was observed at the same thermocouple positions, the thermocouple position 3. The thermal predictions at thermocouple position 3 on the solid web for all cases are presented in Figure 10. It is seen that the predicted temperatures are higher for the case with lesser centre-to-centre spacings of the openings and vice versa. This is because of the width of the solid steel web, which is smaller for closely spaced openings and larger for widely spaced openings. The predicted temperatures are higher for smaller widths of the solid steel web and lower for larger steel web widths. These results show that for smaller opening spacings, the temperatures under the web openings as well as those on the adjacent solid steel web are higher in comparison to the case where the spacing of the web openings are larger. Hence, for slim floor beam with closely spaced web openings, higher temperatures are produced on the steel web under the openings as well as on the adjacent steel web which presents a more severe case. In case where the spacings of the openings are larger, temperatures under the web are higher but the temperatures predicted for the solid steel web are lower resulting in a less severe case.

5.2 Sensitivity studies on the size of openings

During this part of the sensitivity study, the size of the openings was different in each investigated case while the openings were positioned along the centreline of the steel web as before. Further, these openings were positioned in such a way that the minimum width of the solid web between the openings was 100 mm, same in all cases. Because of variations in the size of the openings, depth of the solid web above and below the openings was different in each case. For the case with 50-mm-sized openings, the depth of the steel web above and below the opening was 69 mm, while for the case with 70-mm-sized openings, this was 59 mm. In case of the slim floor beam with 100 mm web openings, the size of steel web above

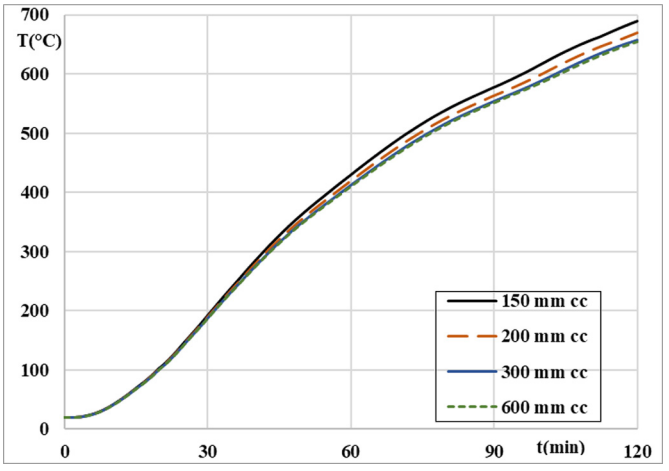


Figure 10.
Predicted temperatures at the thermocouple position 3 on the solid steel web for different centre-to-centre spacings of web openings

and below the opening was 44 mm; however, for the case with 130-mm-sized web openings, this depth was only 29 mm. The thermal results from the analysis after 120 min of standard fire exposure are presented in Figure 11. The thermal contours in Figure 11 show that the temperatures on the parts of the steel web above and below the openings are influenced because of the variations in the size of web openings. However, the temperatures predicted on the solid steel web between the openings are less influenced by their similar widths.

Temperature variations on the steel web are presented in terms of the temperature differences at the openings and on the solid steel web for thermocouple positions 3 and 5 in Figure 12(a) and 12 (b), respectively. These temperature differences presented are the ones predicted on the steel web above and below the openings and at the adjacent solid steel web and at similar thermocouple positions. The temperature differences on the lower parts of the steel web are highest for the largest opening size, the case with 130 mm diameter openings. However, these differences are minimum for the case where the size of the web openings is the smallest, as shown in Figure 12(a). The temperatures predicted below the web openings are higher compared to those predicted for the adjacent solid steel web in all cases. However, the temperatures predicted on the solid steel web are higher compared to those predicted on the steel web above the opening at thermocouple position 5, as shown in Figure 12(b).

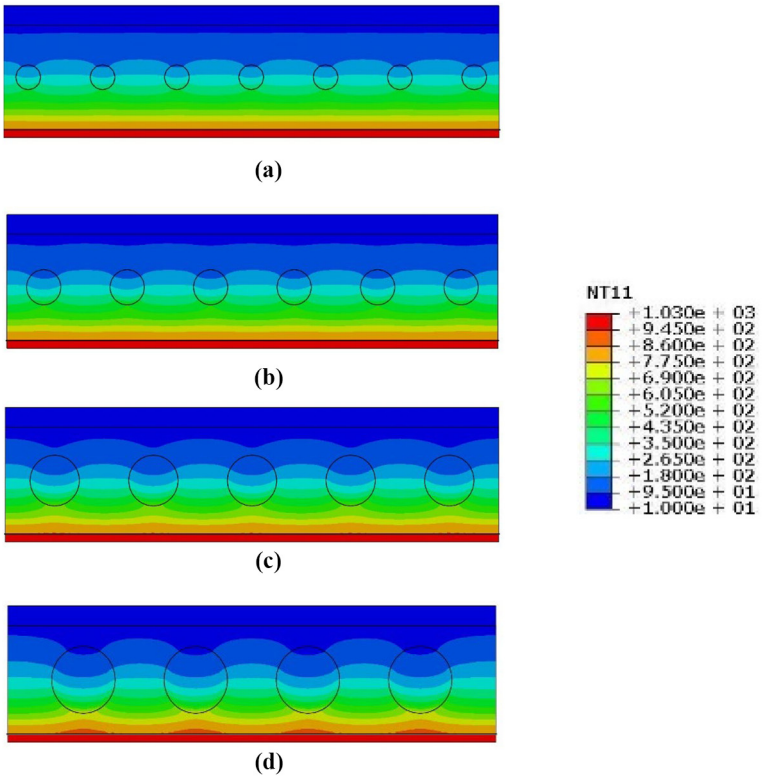
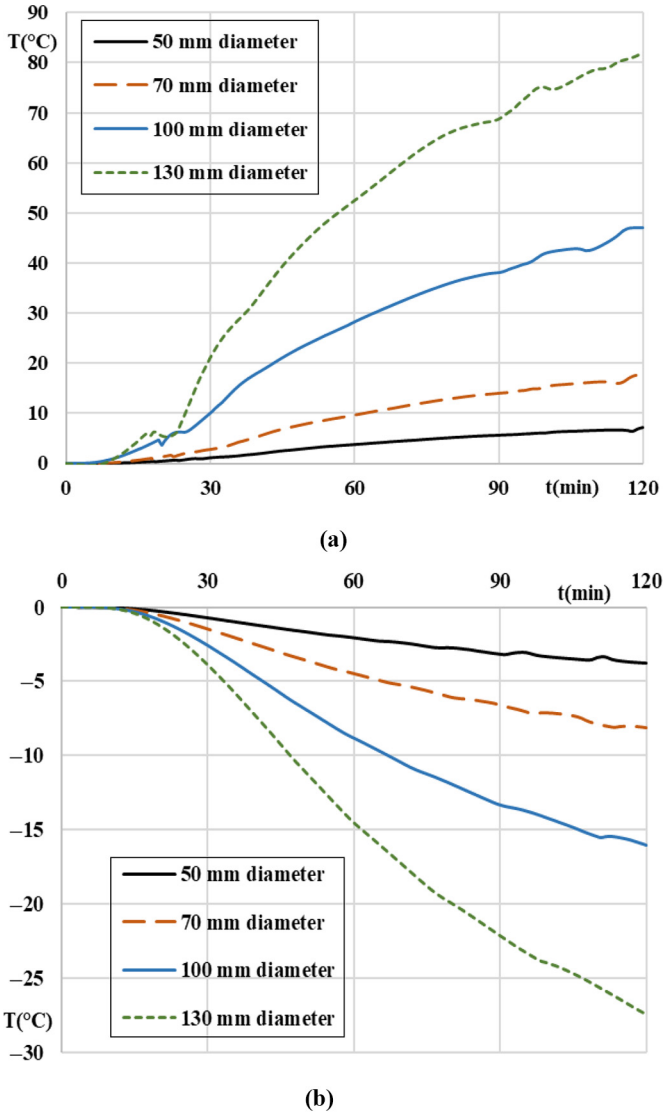


Figure 11.
Thermal contours and analytical results on the influence of the size of web openings

Notes: (a) 50 mm diameter openings; (b) 70 mm diameter openings; (c) 100 mm diameter openings; (d) 130 mm diameter openings



Notes: (a) For thermocouple positions 3; (b) for thermocouple positions 5

Figure 12. Temperatures differences on the steel web at openings and on the adjacent solid steel web for different opening sizes

Similar to the bottom part of the web, the difference in the predicted temperatures are higher for larger opening sizes compared to smaller sizes. These results show that severe temperature distributions are produced in slim floor beams with larger web opening sizes in comparison with the beams with smaller web opening sizes.

Because of the change in the size of the web openings, the depth of the steel web above and below the opening was different for each slim floor beam assembly. To analyse the influence of the varying depth of the steel web, the predicted temperatures on the lower part of the steel web, at 20 mm from the inner side of the bottom flange, are presented in Figure 13. It can be seen that the predicted temperatures on the bottom part of the steel web under the openings are higher for larger sizes of the web openings compared to those for smaller sizes. Hence, larger web openings produce more severe temperature distributions compared to the smaller web openings in slim floor beams exposed to fire.

5.3 Sensitivity studies on the shape of openings

The sensitivity study on the opening shapes consists of four cases. The first case consisted of a slim floor beam with 100 mm diameter circular web openings while the second case consisted of 100 mm square shaped web openings. Keeping in view the opening shapes currently used for cellular composite beams, slim floor beams with elongated and rectangular web openings were also investigated. These shapes were included in the analysis anticipating their possible future use in slim floor constructions. The elongated openings were 100 mm deep and 300 mm long with semi circles of 100 mm diameter at each end. The rectangular web openings investigated were 100 mm deep and 300 mm long. All these openings were aligned with the geometric centre of the steel web, which resulted in 44 mm deep steel web above and below the openings. Further, in all cases the minimum width of the solid steel web was kept similar and was 100 mm between the edges of the openings. Results from the analysis obtained after 120 min of standard fire exposure are presented in Figure 14. It can be seen that the shape of the web openings has an influence on the thermal response of these beams when exposed to standard fire. These temperature variations are easily visible from the thermal contours shown in Figure 14 for all slim floor beam cases. Because of the variations in the shape of the openings, the length of the solid steel web below the openings is different for all cases. For the circular openings, this length is just a point and changes along its length. For the square openings, the length of the web below the opening is 100 mm; however, for the rectangular openings, this length is 300 mm.

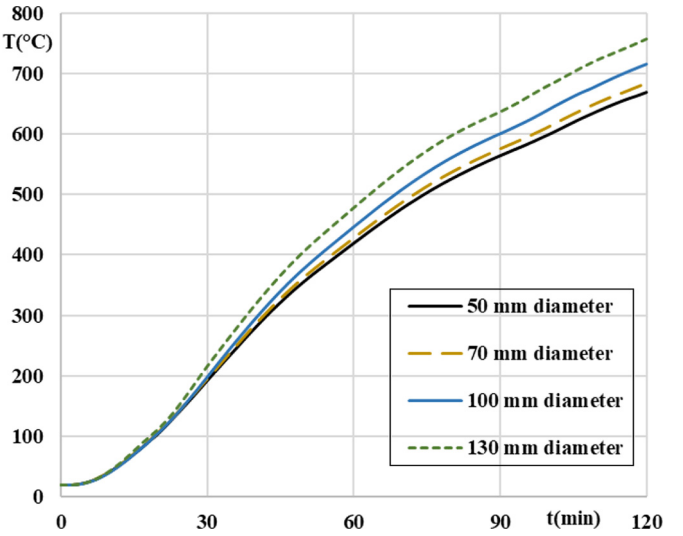


Figure 13.
Predicted temperatures at thermocouple position 3 on steel web under the openings for slim floor beams with different opening sizes

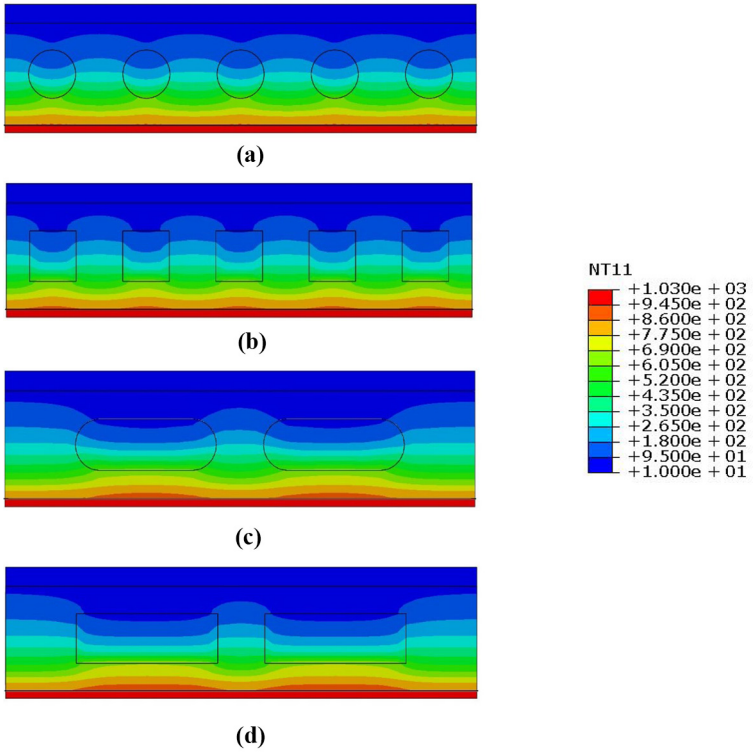


Figure 14.
Thermal contours and analytical results on the influence of opening shapes

Notes: (a) 100 mm diameter circular openings; (b) 100 mm square openings; (c) 300 mm elongated openings; (d) 300 mm rectangular openings

In case of elongated openings, the length of the steel web below the openings is 200 mm, as shown in Figure 7.

The results from the analytical investigation are presented in terms of the temperature differences on the web at the centreline of the openings and those on the adjacent solid steel web in Figure 15. The results presented in Figure 15(a) and 15(b) are the temperature differences at section AA and section BB for thermocouple positions 3 and 5. It can be seen in Figure 15(a) that the temperature differences on the bottom parts of the steel web are the lowest for the circular openings as comparted to other investigated opening shapes. These differences are still low for the square shaped openings in comparison to the elongated and the rectangular web openings. The differences in temperatures for the rectangular openings were found to be the highest, as shown in Figure 15(a). Similar pattern of thermal differences was observed on the upper parts of the steel web where the temperatures on the solid part of the steel web were higher compared to those predicted on the adjacent steel web above the openings, i.e. thermocouple position 5. These differences were highest for rectangular openings and lowest for circular openings, as shown in Figure 15(b).

To analyse the influence of the variations in the length of the steel web below the openings resulting from different opening shapes, temperatures predicted at the centreline of the openings at thermocouple position 3 below the openings at section BB¨ are presented

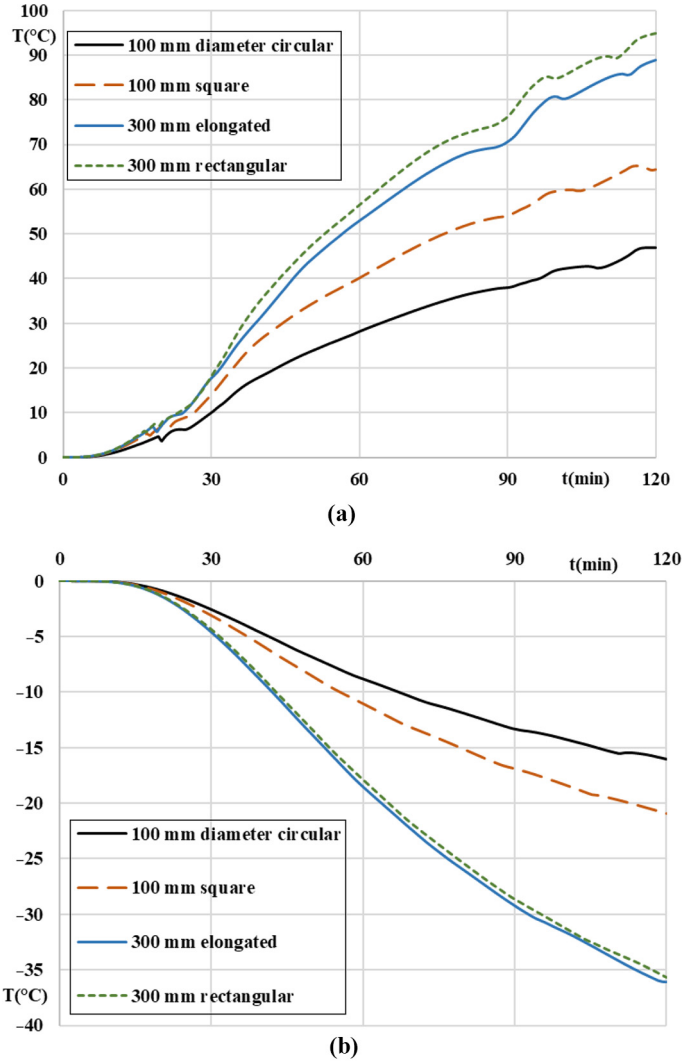


Figure 15.
Temperatures differences on the steel web at openings and on the adjacent solid steel web for different shapes of web openings

Notes: (a) For thermocouple positions 3; (b) for thermocouple positions 5

in Figure 16. The predicted temperatures at thermocouple position 3 are the lowest for the circular web openings. These predicted temperatures on the same parts of web are higher for square shaped openings compared to circular openings and are lesser in comparison with those predicted for elongated and rectangular shaped openings. The predicted temperatures in case of the rectangular openings were found to be the highest while those predicted for the elongated openings were very close to the ones predicted for rectangular openings. These results show that the temperature distributions for slim floor beams with

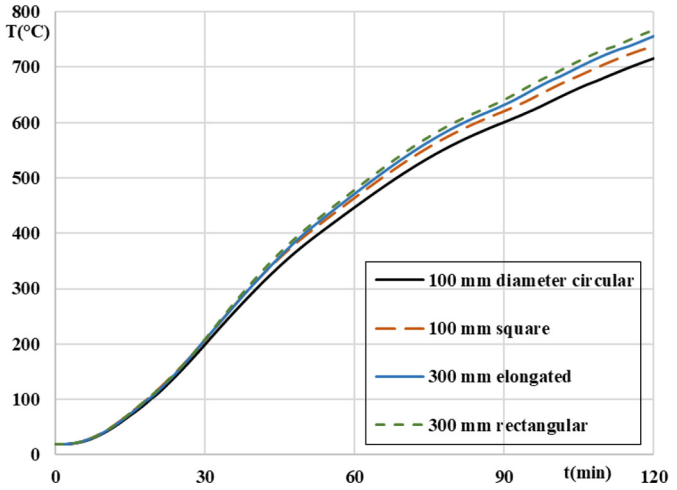


Figure 16.
Predicted temperatures at the thermocouple position 3 on the steel web below the openings for different web opening shapes

rectangular and elongated web openings are the most severe while for those with circular web openings these are the least severe.

6. Conclusions

This research presents the findings from an experimental and an analytical investigation conducted to study the influence of the web openings on thermal behaviour of slim floor beams in fire. Some conclusions from the research are listed below:

- During the experimental investigation, it was found that the presence of web openings has a considerable influence on the thermal behaviour of slim floor beams in fire. It was observed that the presence of the web openings induces higher temperatures on the parts of web below the openings compared to those on the adjacent solid steel web.
- The behaviour of the slim floor beam from the fire test was replicated using finite element modelling with the purpose to conduct a sensitivity study.
- During the sensitivity study, it was observed that smaller centre-to-centre spacing of openings develops more severe temperature distributions compared to larger spacing of openings. The closer arrangement of the web openings produces higher temperatures on the steel web below the openings as well as on the adjacent solid steel web. This is the result of the reduced size of the solid steel web width in case of closely spaced openings.
- Investigations on the influence of the opening sizes show that the temperature differences on the bottom part of the steel web, under the openings and on the adjacent solid steel web, are more severe for larger opening sizes compared to those for smaller openings. This is because of the reduction in depth of the steel web under the opening resulting from an increase in their size.
- The investigation on shapes of the openings shows that the presence of the circular web openings produces less severe temperature distributions compared to square, elongated and rectangular web openings. The rectangular web openings were found to produce the most severe temperature distributions on the slim floor beams.

Hence, opening spacings, sizes and shapes were found to have an influence on the thermal response of slim floor beams in fire.

- The results from this study show that the presence of web openings has a considerable influence on the thermal behaviour of slim floor beams in fire. Closely spaced, large and rectangular openings have a more severe influence on their thermal behaviour compared to widely spaced, small and circular web openings. Such interventions and design fabrications in slim floor beams required due attention in relation to their fire response. In cases where designs with web openings are required, the shape of the openings should be kept small and circular and should be fabricated at larger centre-to-centre spacings.

The current investigation addresses only the thermal behaviour of slim floor beams with web openings in fire. It is early to conclude the influence of these openings on mechanical response of slim floor beams in fire at this stage. Slim floor beams designs are still evolving, and further experimental and analytical investigations are required to analyse any influence of web openings on mechanical response of slim floor beams exposed to fire.

References

ABAQUS (2016), *Finite Element Modelling Programme and Standard User's Manual*, Version 6.14. SIMULIA.

Alam, N., Nadjai, A., Ali, F. and Nadjai, W. (2018a), "Structural response of unprotected and protected slim floors in fire", *Journal of Constructional Steel Research*, Vol. 142, pp. 44-54, available at doi: http://dx. doi.org/10.1016/j.jcsr.2017.12.009.

Alam, N., Nadjai, A., Maraveas, C. and Tsavdaridis, K.D. (2018b), "Response of asymmetric slim floor beams in parametric fires", *Journal of Physics: Conference Series. European Symposium on Fire Safety Science (ESFSS 2018)*, 12-14 Sep 2018, Nancy.

Alam, N., Nadjai, A., Maraveas, C., Tsavdaridis, K.D. and Kahanji, C. (2018c), "Effect of air-gap on response of fabricated slim floor beams in fire", *Journal of Structural Fire Engineering*, available at: https://doi.org/10.1108/JSFE-04-2018-0011

British Standards Institution (1987), "BS 476 part-20:1987. (2012). fire tests on building materials and structures", Method for determination of the fire resistance of elements of construction (general principles).

De Nardin, S. and El Debs, A.L.H.C. (2009), "Study of partially encased composite beams with innovative position of stud bolts", *Journal of Constructional Steel Research*, Vol. 65 No. 2, pp. 342-350, available at doi: http://dx. doi.org/10.1016/j.jcsr.2008.03.021.

European Committee for Standardization (2008), "BS EN 1992-1-2 Eurocode 2: design of concrete structures part 1-2 general rules – structural fire design", European Committee for Standardization.

European Committee for Standardization (2009a), "BS EN 1993-1-2 eurocode 3: Design of steel structures, part 1-2, general rules – structural fire design", European Committee for Standardization.

European Committee for Standardization (2009b), "EN1991-1-2, eurocode 1 – actions on structures – part 1–2: General rules –structural fire design", European Committee for Standardization.

European Committee for Standardization (2014), "BS EN 1994-1–2: Eurocode 4: Design of composite steel and concrete structures - General rules – structural fire design", European Committee for Standardization, Vol. 3.

Huo, B.Y. and D'Mello, C.A. (2013), "Push-out tests and analytical study of shear transfer mechanisms in composite shallow cellular floor beams", *Journal of Constructional Steel Research*, Vol. 88, pp. 191-205. available at: http://dx.doi.org/10.1016/j.jcsr.2013.05.007

International Standards Organization (1999), *ISO 834-1, Fire Resistance Tests-Elements of Building Construction. Part 1: General Requirements*, International Standards Organization.

Maraveas, C., Swailes, T. and Wang, Y. (2012), "A detailed methodology for the finite element analysis of asymmetric slim floor beams in fire", *Steel Construction*, Vol. 5 No. 3, pp. 191-198.

Maraveas, C., Tsavdaridis, K.D. and Nadjai, A. (2016), "Fire resistance of unprotected ultra shallow floor beams (USFB): a numerical investigation", *Fire Technology*, Vol. 53 No. 2, pp. 609-627, available at: https://doi.org/10.1007/s10694-016-0583-5

Mullet, D.L. (1998), *Composite Floor Systems*, 1st ed., The Steel Construction Institute, London.

Newman, G.M. (1995), "Fire resistance of slim floor beams", *Journal of Constructional Steel Research*, Vol. 33 Nos 1/2, pp. 87-100, available at: http://dx.doi.org/10.1016/0143-974x(94)00016-b

Tsavdaridis, K.D. and D'Mello, C. (2012), "Vierendeel bending study of perforated steel beams with various novel web opening shapes through nonlinear finite-element analyses", *Journal of Structural Engineering*, Vol. 138 No. 10, pp. 1214-1230, available at: http://dx.doi.org/10.1061/(asce)st.1943-541x.0000562

Tsavdaridis, K.D., D'Mello, C. and Huo, B.Y. (2013), "Experimental and computational study of the vertical shear behaviour of partially encased perforated steel beams", *Engineering Structures*, Vol. 56, pp. 805-822, available at: http://dx.doi.org/10.1016/j.engstruct.2013.04.025

Corresponding author
Naveed Alam can be contacted at: n.alam@ulster.ac.uk

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**