

Fire design of composite beams with web openings protected with reactive intumescent coating

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ABSTRACT

When service ducts and cables are required to pass through the structural beams, it is a common practical solution to use composite beams with rectangular or circular openings. The fire safety standards in many countries have recommended design methods for composite beams without openings, while the design method for composite beams with web openings is not addressed yet. Due to the complicated distribution of temperature and stress around the openings in the web of the steel beam, extra complexity has been introduced in determination of the structural capability of the beam and the failure mode in fire.

These failure modes generally occur at lower limiting temperatures than the solid beam with same size. It is recognized that the thickness of a reactive coating required to provide a given fire resistance to a composite beam with web openings is affected by the beam's web thickness, opening configuration, the degree of the beam asymmetry and the structural utilization factor, as well as the nature of the proprietary fire protection itself. Therefore it is necessary that such beams are structurally evaluated taking into account all possible modes of structural failure under both ambient and fire conditions. It is also necessary for additional thermal data to be measured around the web openings and on the web posts from fire tests. The additional thermal data will be used in conjunction with a structural model to determine limiting temperatures of beams with web openings.

Steel Construction Institute (SCI) have produced a structural analysis model referenced as report RT1356, which divides a composite beam with web openings into different stress blocks, and then analyses the global bending, vertical shear, local Vierendeel bending, web-post buckling etc. The Association for Specialist Fire Protection (ASFP) recommended the test protocol in the Yellow Book, to determine the temperature distribution around the openings and web post.

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This paper will discuss a series of fire tests have been carried out in the laboratory of EXOVA Warringtonfire to establish temperature distribution in composite beams with web openings. Test result shows that the distribution of temperature is product specific and strongly affected by opening configuration and opening distance. EXOVA Warringtonfire has also developed a sophisticated calculator, ThermCalc, for analyzing temperature and structural following the method presented in RT1356. Using ThermCalc, parametric study has been carried out, and the effect of load utilization factor, opening size, opening distance, slab depth, decking configuration etc. was investigated.

Key words: Fire safety, composite beam, web opening, cellular beam

1 Introduction

When service ducts and cables are required to pass through the structural beams, it is a common practical solution to use composite beams with rectangular or circular openings in the web. Many fire design methods for composite beams without openings have been recommended in fire safety standards from many countries. When designing composite beams with web openings, additional features need to be considered, such as the non-uniform temperature distribution, Vierendeel action, buckling of web post, etc.

The Steel Construction Institute (SCI) was commissioned by the Association for Specialist Fire Protection (ASFP) to produce a fire design guidance for composite beams with large web openings, which has been published in February 2014 referenced as RT1356 (SCI 2014). The methodology includes some of the guidance presented in *SCI publication Design of Composite Beams with large web openings*(P355) (Lawson et al 2011), which was developed on the basis of a European research project (Lawson et al 2006).

It is recognized that the temperature distribution in the composite beams with web openings is affected by the beam dimensions, opening configurations, and the fire product, etc. ASFP recommended a test protocol in the Yellow Book (ASFP 2014) to determine temperature ratios relating the temperature around web opening to web reference temperature. This was known as the assessment of the web post line and was used together with the solid beam assessment to give an appropriate protection thickness. The result of a series of test will be discussed in this paper.

Exova Warringtonfire developed a computer program ThermCalc, based on the structural analyzing model (RT1356) and temperature distribution data (according to ASFP Yellow Book 2014). Using ThermCalc, parametric study was carried out, and the effect of load utilization factor, opening size, opening distance and web thickness has been investigated.

2 Temperature zones

As the temperature distribution in the composite beams with web openings is not uniform, in the structural analyzing model, a composite beam is divided into 7 zones, which consist of:

- Zone 1: bottom flange
- Zone 2: solid web away from openings
- Zone 3: web post between openings
- Zone 4: web below opening
- Zone 5: web over opening
- Zone 6: top flange
- Zone 7: concrete slab

It is assumed that within each zone the temperature is uniform. The temperature may be different from one zone to another.

3 Structural analyzing mode

In composite beams with web openings, various modes of failure may occur at or around large openings. Besides bending failure, vertical shear or Vierendeel failure may occur due to local effects around single large openings, and web post bending or buckling failure may arise between closely spaced openings. All the possible failure modes are illustrated in Figure 1.

In RT1356 (SCI 2014), methods are presented to check the above failure modes at elevated temperature, considering the effect of temperature at different zone.

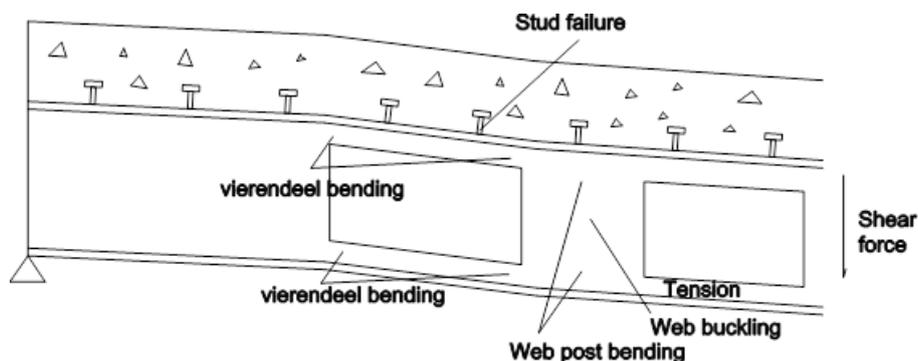


Figure 1 Structural failure model

4 Fire test and assessment to determine temperature distribution

4.1 Test design

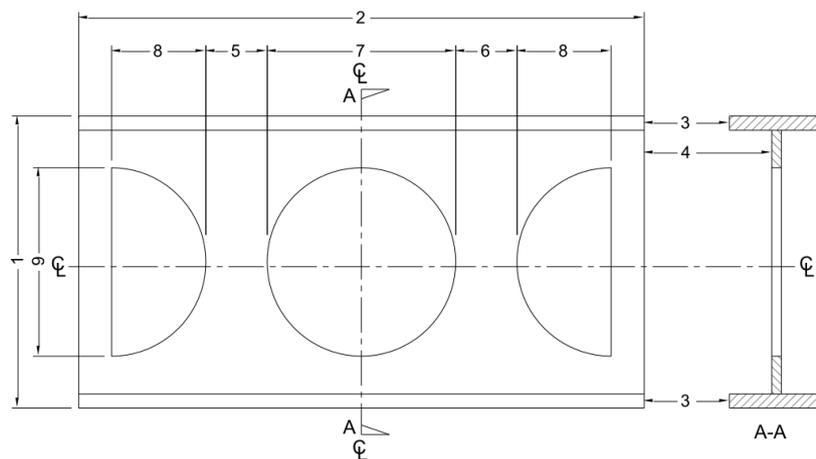
ASFP recommended a test protocol for composite beams with web openings in the Yellow Book 5th Edition (ASFP 2014), which was based on determining temperature

ratios relating the temperature around web opening to the web reference temperature.

Each test program will include minimum 5 short sections. with circular openings and rectangular openings. The scope of the assessment will determine the dimension of the short sections. The web post width varies normally from 130mm (can be narrower depending on design requirements) to 500mm. The layout of the openings is illustrated in Figure 2 and Figure 3. Thermocouples will be installed in web post (Position A, B, C, D, E), web over and lower openings (Position J, K, L, M, O, P) to measure the temperature from different zones.

4.2 Web line assessment

The web post line assessment shall be based on the ratio of the mean web post temperature (at Position A, B, C, D) to the web reference temperature. The web reference temperature is calculated as the average of the four thermocouples referred to as E in Figure 5.

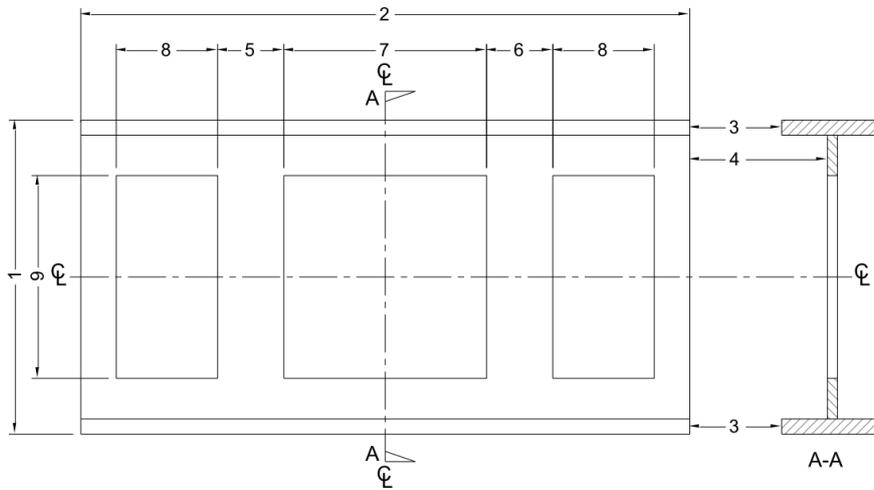


Dimensions in figure

Specimen (Tables 12 - 14)	1	2	3	4	5	6	7	8	9
1	600	1200±50	170x12	8 thick	130	160	400	200	400
2	600	1200±50	170x12	8 thick	160	225	400	200	400
3	600	1200±50	170x12	8 thick	130	225	400	200	400
6	600	1200±50	170x15	10 thick	130	160	400	200	400
7	600	1200±50	170x15	10 thick	160	225	400	200	400
8	600	1200±50	170x15	10 thick	130	225	400	200	400
11	600	1200±50	170x20	12 thick	130	160	400	200	400
12	600	1200±50	170x20	12 thick	160	225	400	200	400
13	600	1200±50	170x20	12 thick	130	225	400	200	400

Dimensions in mm

Figure 2 Dimensions of specimen with circular openings

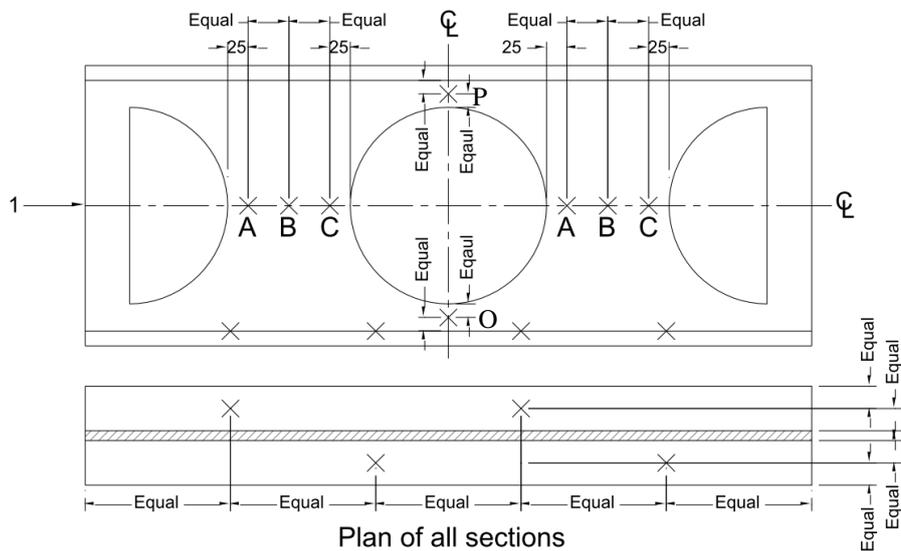


Dimensions

Specimen (Tables 12 - 14)	1	2	3	4	5	6	7	8	9
5	600	1200±50	170x12	8 thick	130	225	400	200	400
10	600	1200±50	170x15	10 thick	130	225	400	200	400
15	600	1200±50	170x20	12 thick	130	225	400	200	400

Dimensions in mm

Figure 3 Dimensions of specimen with rectangular openings



Plan of all sections

Figure 4 Thermocouples in specimen with circular openings

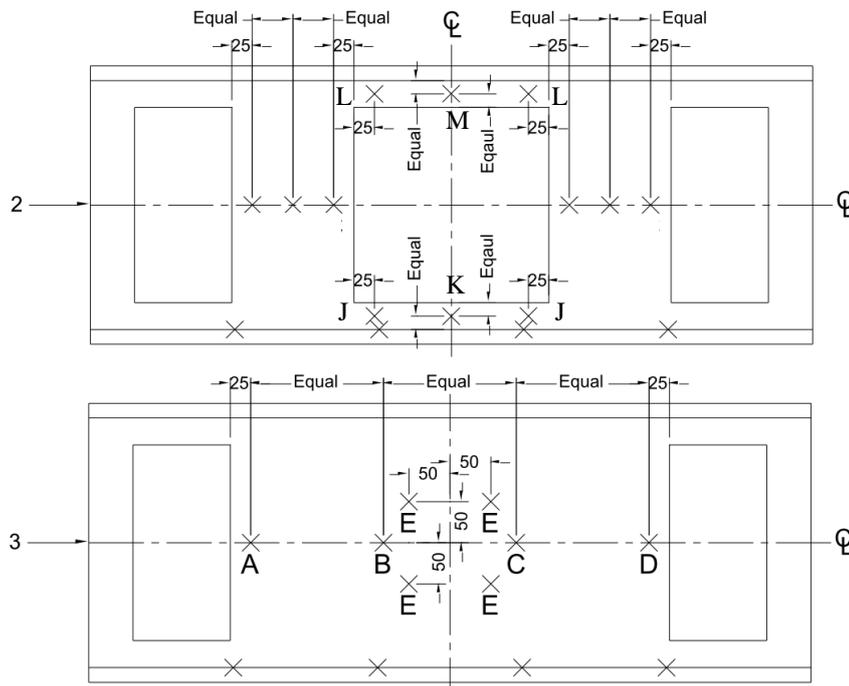


Figure 5 Thermocouples in specimen with rectangular openings

4.3 Additional thermal modification factors

In addition to the thermocouples at the web post, additional thermocouples are fixed at the web over or beneath the openings (Position J, K, L, M, O, P in Figure 4 and Figure 5). These measurements can be used to calculate further modification factors as the ratio to the web reference value.

5 Fire test result

Many fire tests on composite beams with different intumescent coating products have been carried out in Exova Warringtonfire laboratory. Test results show the web line ratio and the additional thermal modification factors vary with different protection products. The web line data and additional thermal modification factor of one example intumescent coating product are shown in Table 1 and Table 2.

Table 1 Web line data

Circular Openings		Rectangular Openings	
Web post width (mm)	Web post ratio	Web post width (mm)	Web post ratio
130	1.2	130	1.2
150	1.0	200	1.2
Over 150	1.0	250	1.1
		550	1.0

Table 2 Additional thermal modification factor

Position	Point ratio
K	1.0
L	1.0
M	0.9
N	0.8
O	1.0
P	0.8

6 The fire design software ThermCalc

Exova Warringtonfire has developed a sophisticated calculator, ThermCalc, for temperature and structural analysis following the method presented in RT1356. It consists of a GUI module (Graphical user interface) to create and modify the composite beam model, and a calculating module to analyzing the beam at ambient temperature and elevated temperature. Finally it can work out the critical temperature and the protection thickness, depending on which protection product is used. The interface of ThermCalc is shown in Figure 6.

An iteration method on protection thickness (ASFP 2014) has been employed in analyzing the composite beams, as shown in Figure 7.

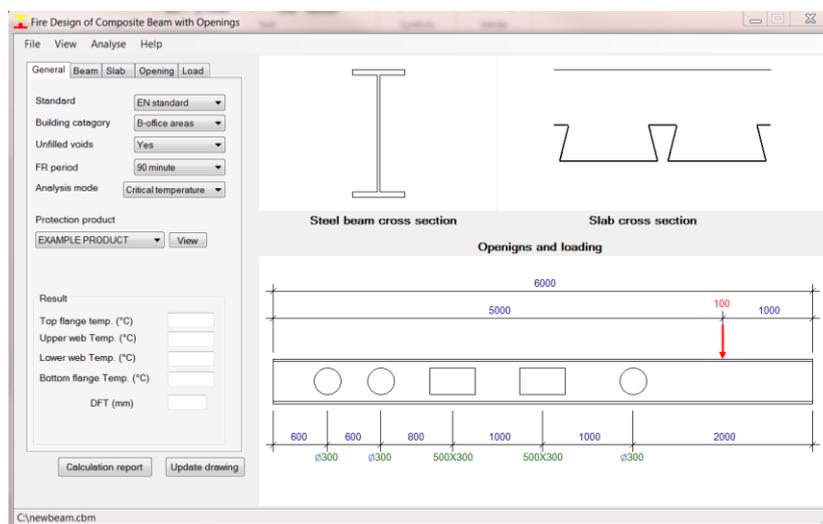


Figure 6 ThermCalc user interface

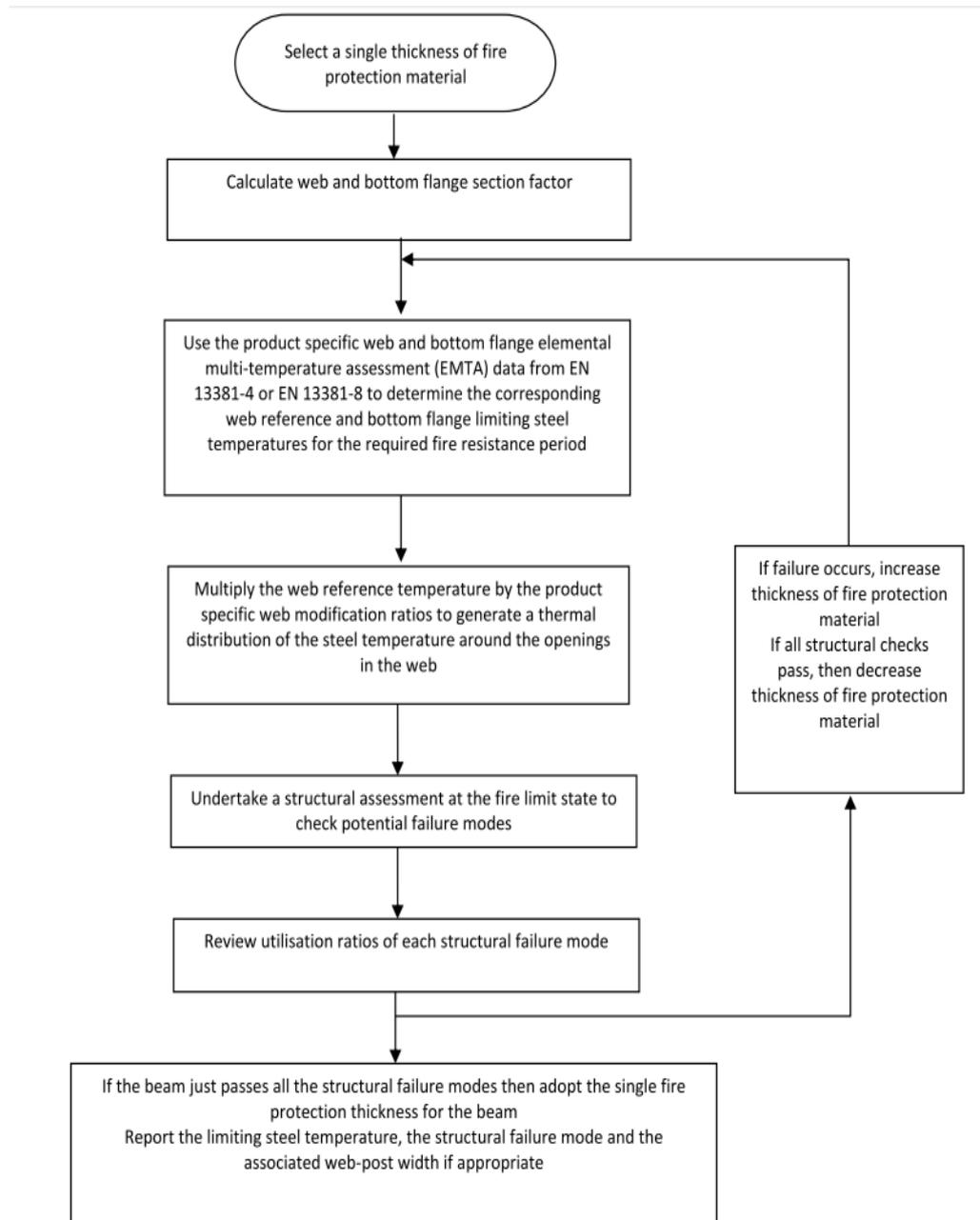


Figure 7 Iteration method in the analysis

7 Parameter study

7.1 General design of the composite beams

In order to study the effect of different parameters of composite beams on the fire resistance performance, a series of composite beams with different configurations have been analyzed using ThermCalc. The general information of the composite beam are listed in Table 3.

Table 3 General information of the composite beams

Beam span:	8000 mm
Steel section height:	500 mm
Flange width:	300 mm
Flange thickness:	20 mm
Web thickness:	12 mm
Slab thickness:	140 mm
Slab concrete grade:	Normal weight C30/37
Decking type:	Metfloor 60 Trapezoidal
Decking thickness:	0.9mm
Opening diameter:	350 mm

The web post line data in Section 6 was used together with the solid beam assessment to determine the temperature distribution.

7.2 Utilization factor

Utilization factor indicates that to what extent of the load bearing capacity of a structural member has been utilized to bear the design load. When only uniformly distributed loads are applied on a structural member, the utilization factor can be defined as the ratio of the design load to the maximum load at limit state. When the loads consist of different types of loads, e.g. pointed load and distributed load, the utilization factor can also be interpreted as the stress ratio, which is the ratio of stress under design load to the design strength of the material.

Generally, a structural member with lower utilization factor will have higher critical temperature in fire condition. Investigation shows it also applies to composite beams with web openings. In the following parameter study, the utilization factors of all the beams are 1.0, unless other value is stated separately.

7.3 Effect of Centre distance of opening

As the width of web post between openings is one of most important factor affecting the bulking resistance of web post, 5 composite beams with different web post width have been analyzed. The utilization factor is 1.0. The openings are circular with 350 mm diameter. The ratio (s_0/D) of web post width to the opening diameter and critical temperature are listed in Table 4.

Table 4 Critical temperature with different web post width

Name	s_0/D	Critical temperature (°C)
C-1	0.5	600
C-2	1.0	619
C-3	1.5	636
C-4	2.0	640

It shows that when the web buckling is in control the beam with wider web post has higher critical temperature.

7.4 Effect of opening size

The size of opening also has significant effect on the fire resistance performance of composite beams. A composite beam with $\varnothing 300$ mm openings is analyzed and the critical temperature is compared to C-1, of which the opening diameter is 350 mm. The web post width in both beams is 350 mm. The result is listed in Table 5.

Table 5 Effect of opening size

Name	Opening diameter (mm)	Critical temperature (°C)
C-2	350	619
C-2-S	300	609

Surprisingly, the composite beam with small size has lower critical temperature. This is because the beams both have same utilization factor 1.0. At room temperature, Beam C-2-S has greater load bearing capacity due to small opening size. In fire condition, the improvement of loading bearing capacity due to smaller size is not as great as that in room temperature, which leads to lower critical temperature. Therefore when the composite beams with different opening sizes have same utilization factor, the beam with small opening may have lower critical temperature.

7.5 Effect of opening type

Generally, the web post between circular openings has better buckling resistance compared to the web post between rectangular openings, as the space at the top and bottom goes wider between circular openings.

For composite beams with rectangular openings, when the Vierendeel takes control, the width/height of opening may affect the critical temperature. 3 composite beams with different rectangular sizes are analyzed and the results are list in Table 6.

Table 6 Effect of rectangular opening size

Name	Opening size (w x h)	Critical temperature (°C) of beams with	
		web post width is 350 mm	web post width is 700 mm
R-1	350x350	566	609
R-2	350x525	566	629
R-3	350x700	552	609

It shows that if the utilization factors are same, beams with narrower opening may not always have higher critical temperature, due to the similar reason explained in section 7.4.

7.6 Effect of web thickness

A series of composite beams with different web thickness have been studied. The openings are rectangular with size 350x350 mm. The web post width is 350 mm. the results are shown in Table 7.

Table 7 Effect of web thickness

Name	Web thickness (mm)	Critical temperature (°C)
W-1	10	496
W-2	12	566
W-3	14	610
W-4	16	636

It shows that the composite beam with thicker web has higher critical temperature.

8 Conclusion

The fire design and fire test method of composite beams with web openings has been introduced in this paper. A series of composite beams with web openings have been analyzed using the software ThermCalc, to study the effect of different parameters of composite beams on the fire resistance performance. It shows that

1. When the web buckling is in control the beam with wider web post will have higher critical temperature.
2. When utilization factors are same, the beam with small opening may has less critical temperature; beams with narrower opening may not always have higher critical temperature.
3. The composite beams with thicker web will have higher critical temperature.

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