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Analysis of behaviour of steel beams with web openings at elevated temperatures

Y. Z. Yin†

Ove Arup & Partners HongKong Ltd, Level 5 Festival Walk, 80 Tat Chee Avenue, Kowloon Tong, HongKong

Y. C. Wang‡

School of Mechanical, Aerospace and Civil Engineering (MACE), The University of Manchester, Manchester M60 1QD, UK

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Abstract. Beams with web openings are an attractive system for multi-storey buildings where it is always desirable to have long spans. The openings in the web of steel beams enable building services to be integrated within the constructional depth of a floor, thus reducing the total floor depth. At the same time, the increased beam depth can give high bending moment capacity, thus allowing long spans. However, almost all of the research studies on web openings have been concentrated on beam behaviour at ambient temperature. In this paper, a preliminary numerical analysis using ABAQUS is conducted to develop a general understanding of the effect of the presence of web opening on the behaviour of steel beams at elevated temperatures. It is concluded that the presence of web openings will have substantial influence on the failure temperatures of axially unrestrained beams and the opening size at the critical position in the beam is the most important factor. For axially restrained beams, the effect of web openings on the beam's large deflection behaviour and catenary force is smaller and it is the maximum opening size that will affect the beam's response at very high temperatures. However, it is possible that catenary action develops in beams with web openings at temperatures much lower than the failure temperatures of the same beam without axial restraint that are often used as the basis of current design.

Key words: steel beams; opening; elevated temperature.

1. Introduction

Beams with web openings are an attractive system for multi-storey buildings where it is always desirable to have long span. The openings in the web of steel beams enable building services to be integrated within the constructional depth of the floor, thus reducing the total floor depth. At the same time, the increased beam depth can give high bending moment capacity, thus achieving long spans.

†Engineer, Corresponding anthor, E-mail: yinyz@hotmail.com
‡Reader, E-mail: yong.wang@manchester.ac.uk

Most beams with web openings can be classified into two types (Liu and Chung 2003)

- Hot-rolled steel beams with single web opening: this type of section normally consists of a rectangular web opening with the aspect ratio ranging from 1~3. The opening depth is usually restricted to 1/2 of the overall section height.
- Fabricated beams with multiple web openings: this type of section has increased depth for better structural performance against bending, and normally consists of web openings with depth up to 2/3 of the overall section height.

Recently, it has become more and more popular to use larger web openings with depth up to 3/4 of the overall section height and cellular beams with multiple openings for easy installation of building services.

Thus, many research efforts have been devoted to studying the effect of web openings on beam behaviour (Redwood and Cho 1993, Chung *et al.* 2001, 2003, Liu and Chung 2003), in which the effect of shapes, sizes and locations of the web openings are investigated so as to achieve optimal design to minimise total construction cost. However, almost all of the research studies on web openings are concentrated on beam behaviour at ambient temperature. In this paper, a brief analysis is conducted to develop a general understanding of the effect of the presence of web opening on the large deflection behaviour and catenary action of steel beams at elevated temperatures.

2. Validation of ABAQUS simulations

Shell element S4R in finite element software ABAQUS (2001), is used to model the steel beam. The sensitivity of the numerical results to the mesh size has been studied in the previous studies (Yin and Wang 2003). In this study, for combined accuracy and computational economy, the beam flange is divided into four shell elements and the web into eight. The number of elements along the beam length is to ensure that the aspect ratio of shell elements is less than 5. The material assumed in the model is Q235 steel and the material properties at ambient temperature and elevated temperatures are based on Eurocode 3 Part 1.2. There are no test results available in published literatures for steel beams with web openings in fire. In order to validate the numerical simulations, a comparison was made with the independent numerical simulation results of Chung *et al.* (2003), who presented results of a large number of finite element simulations on a 12 m UB457×152×52 beam under uniformly distributed

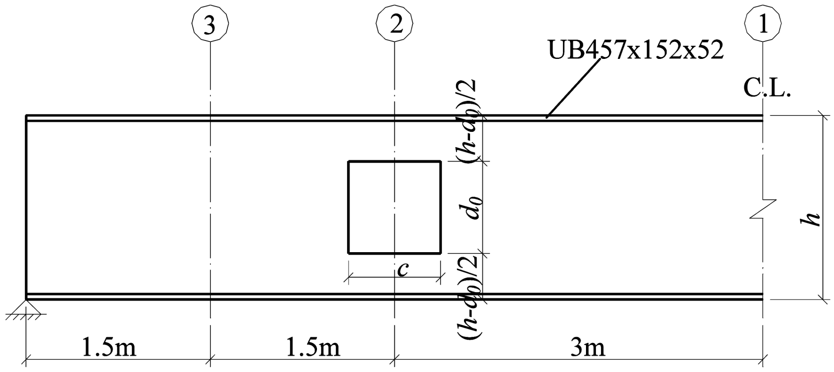


Fig. 1 Selected dimensions and positions of web openings (Chung *et al.* 2003)

Table 1 Comparison of failure loads from results by ABAQUS and Chung *et al.*

Position	d_0	c	Failure load (kN/m)		Difference
			This study	Chung *et al.*	
1	0.75 h	$2d_0$	12.79	13.57	5.7%
2	0.75 h	$2d_0$	9.91	8.74	13.4%
2	0.5 h	d_0	16.69	16.74	0.3%
3	0.5 h	d_0	16.80	16.74	0.4%

load with different rectangular web openings at ambient temperature. The selected dimensions and positions of web openings are shown in Fig. 1. Table 1 compares the failure loads predicted by ABAQUS numerical simulations and the results of Chung *et al.* showing good agreement between the two sets of results.

3. Numerical parametric studies

The objective of this parametric study is to investigate the effects of various influential factors on behaviour of beams with web openings. The effects of the following parameters were considered: single or multiple openings, opening size, location, aspect ratio, temperature distribution and the presence of axial restraint at beam ends.

The steel beam is an 8 m UB457×152×60 beam. It is noticed that beams with web openings are rarely made by simply cutting holes in rolled sections, thus the beam sections adopted in this analysis are not realistic. However, the general conclusions should still hold true.

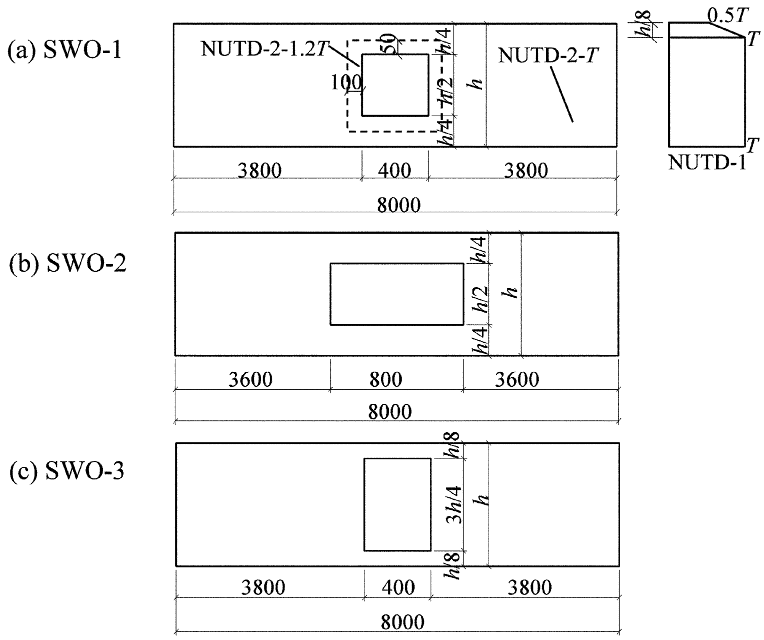
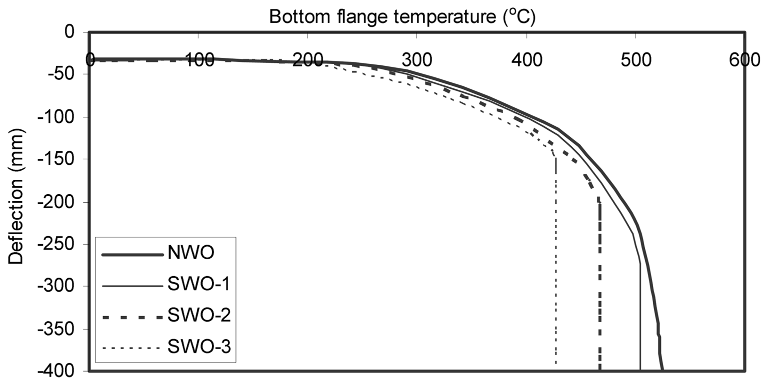


Fig. 2 Dimensions of beams with a single web opening

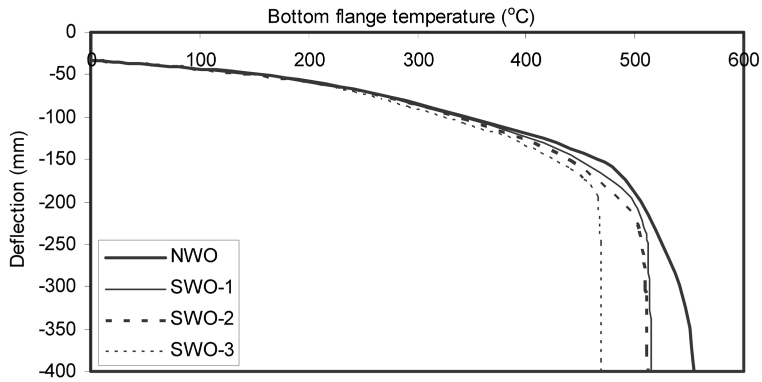
In order to simplify numerical modelling, only rectangular openings are considered in the current analysis. Uniform (UTD), non-uniform temperature distributions NUTD-1 and NUTD-2 as shown in Fig. 2 are applied. For non-uniform temperature distribution NUTD-1, the top flange temperature is half of the temperature of the web and bottom flange. For non-uniform temperature distribution NUTD-2, the steel temperature around the opening is 20% higher than in other places. In order to avoid direct application of point loads at the positions of opening, uniformly distributed load was applied at the top flange of the beam section, with a load ratio of 0.7, defined as the ratio of the externally applied maximum free bending moment in the beam to the bending moment capacity of the full section at ambient temperature. Two types of boundary conditions were simulated, rotationally simply supported beams with and without axial restraint at ends.

3.1. Results for beams with a single web opening

The dimensions for beams with a single web opening are shown in Fig. 2. The single opening is positioned in the centre of the beam span, with different opening depths and widths. SWO-1 and SWO-2 have the same opening depth but the opening width of SWO-2 is twice of that of SWO-1. SWO-1 and SWO-3 have the same opening width with the opening depth of SWO-3 being 3/2 that of SWO-1.



(a) Under uniform temperature distribution



(b) Under non-uniform temperature distribution NUTD-1

Fig. 3 Comparison of the behaviour of beams without and with a single web opening, no axial restraint

3.1.1. No axial restraint

Fig. 3 compares temperature - deflection relationships between axially unrestrained beams without and with a single web opening, in which NWO and SWO represent beams without and with a single web opening respectively.

From Fig. 3, it can been seen that the deflection curves of axially unrestrained beams without or with a single web opening are of the similar shape, with steady deflection increase at low temperatures due to reducing stiffness or thermal bowing or both, then accelerating and runaway deflections when approaching the failure temperatures.

Because there is no axial restraint and the single web opening is at the middle of the beam span where the maximum bending moment is located, it is the bending moment capacity of the cross-section with opening that controls the beam's failure. The effect of a reduction in the beam web depth (by increasing the web opening depth) has the greatest effect since it directly reduces the beam cross-section's bending moment capacity. An increase in the opening width also reduces the beam bending moment resistance due to interaction between local bending at T-section and flexural bending. Thus, the results in Fig. 3(a) is as expected, the deepest web opening (SWO-3) giving the largest reduction in beam failure temperature, followed by the wider web opening (SWO-2). For SWO-1, since the reduction in the web area is small, its effect on beam behaviour is noticeable but relatively small, giving a reduction in beam failure temperature of about 24°C compared to the solid beam. The respective reduction in beam failure temperature for SWO-2 and SWO-3 is 62°C and 102°C.

Under non-uniform temperature (e.g. under NUTD-1 as shown in Fig. 3b), the beam resistance mainly comes from the top flange, which has the lowest temperature. The shear resistance of the top flange/web junction is relatively high so that the interaction between local bending at T-section and flexural bending is not as strong as under uniform high temperatures. Thus, web openings SWO-1 and SWO-2 have the same opening depth and their beam behaviour is similar, with similar reductions in failure temperature of about 44°C and 47°C respectively compared to the solid beam. Opening SWO-3 has a larger depth and its effect on beam behaviour is greater, with a reduction in beam failure temperature of 90°C.

In summary, for beams without axial restraint, web opening has a great effect on beam behaviour and the effects of opening size and aspect ratio can be different depending on the temperature distribution.

Fig. 4 compares the behaviour of beams with a single web opening under uniform temperature distribution (UTD) and under temperature distribution NUTD-2, which has 20% higher temperatures in the region around the opening. The difference of failure temperatures under UTD and NUTD-2 for beams with SWO-1, SWO-2 and SWO-3 are 15°C, 20°C and 32°C respectively. The difference is relatively small for beams with small web openings, but becomes noticeable when the opening size increases.

3.1.2. Full axial restraint

Figs. 5~6 compare the temperature - deflection and temperature - axial reaction relationships for axially fully restrained beams without and with a single web opening.

Compared to the results in Fig. 3, the initial beam deflections for the restrained beams are much greater, as a result of the P-Δ effect. It is noticed that the presence of a web opening will have some effect on the deflection behaviour of steel beams at elevated temperatures, with a beam with larger web opening depths and widths having slightly larger deflections at high temperatures, and the effect of opening depth is larger than that of the width as explained earlier. But the difference in deflection due to a web opening is not enormous, becoming small under non-uniform temperature distribution NUTD-1 as shown in Fig. 6.

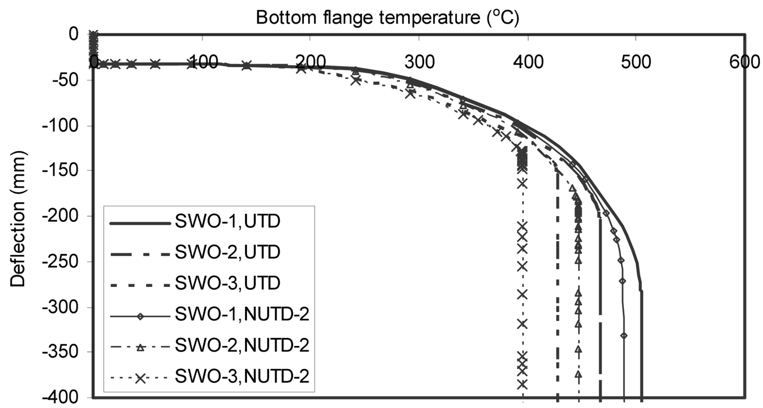
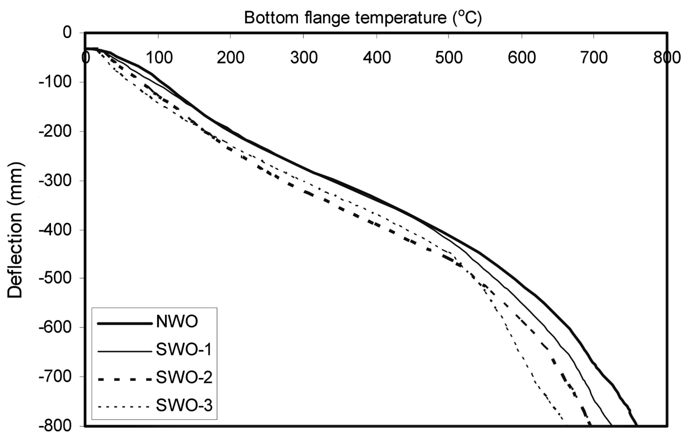
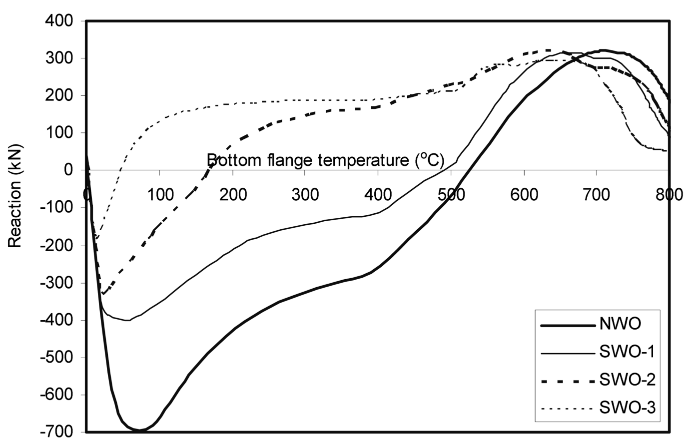


Fig. 4 Comparison of the behaviour of beams with different single web opening, no axial restraint, different temperature distributions

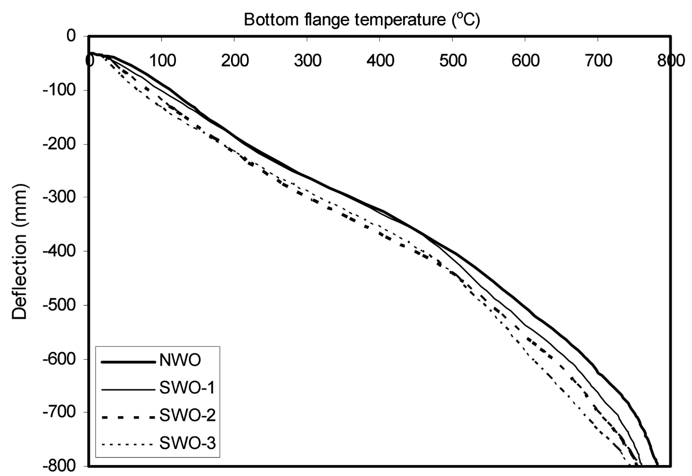


(a) Temperature - deflection relationships

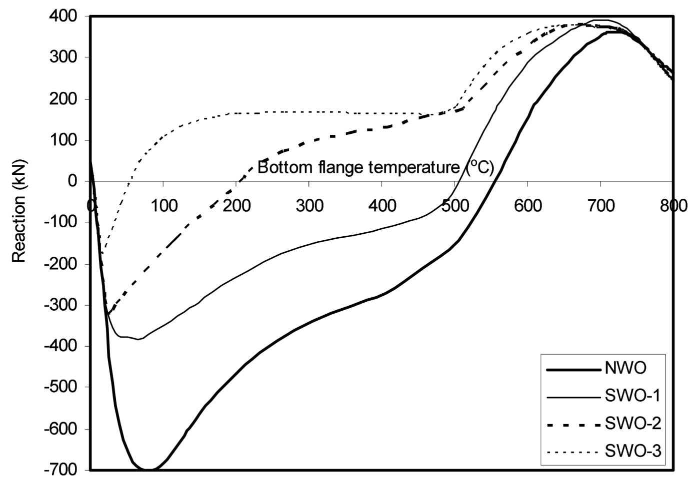


(b) Temperature - axial reaction relationships

Fig. 5 Comparison of the behaviour of beams without and with a single web opening, full axial restraint, uniform temperature distribution



(a) Temperature - deflection relationships



(b) Temperature - axial reaction relationships

Fig. 6 Comparison of the behaviour of beams without and with a single web opening, full axial restraint, non-uniform temperature distribution NUTD-1

The effect of the presence of web openings on the beam's catenary force is relatively small. Due to the presence of the web opening, the beams will reach the maximum catenary force at different temperatures, with the beams with larger web opening reaching the maximum catenary force at lower temperatures because of the smaller bending moment capacity. As can be seen from Fig. 5, the deflection of the beams at the time they reach maximum deflection are almost the same, the maximum beam catenary forces of beams with different web openings are almost identical to that of the beam. The catenary forces after the maximum value decrease to some extent depending on the opening sizes, because under catenary action it is the axial capacity of the beam that determines its behaviour at high temperatures and large deflections.

It can be seen from Figs. 5~6 that the beam's behaviour before attaining the maximum catenary force is greatly affected by the presence of web openings. The larger the opening size, the smaller the maximum beam compression force and the earlier the beam goes into catenary action.

Previous analysis by the authors (Yin and Wang 2004) has shown that for a solid beam, the transit temperature, defined as the temperature at which the axial force in the beam becomes zero, is almost identical to the failure temperature of the same but axially unrestrained beam. This is because for an axially restrained solid beam, the transit temperature occurs at large deflections when the maximum bending moment has become equal to the bending moment capacity of the beam. This is the same mode of behaviour when the axially unrestrained beam has reached its failure temperature.

However for beams with web openings, the transit temperatures are lower than the failure temperatures of the unrestrained beam. For the restrained beams with web opening SWO-1, SWO-2 and SWO-3 under uniform temperature, the transit temperatures are 15°C, 300°C and 380°C lower than the respective failure temperatures of the unrestrained beams. Similar results are also obtained for beams under non-uniform temperature distribution as shown in Fig. 6. This is because the mode of restrained beam behaviour at the transit temperature is now governed by local compression yield of the T-section above the opening, induced by restrained thermal expansion, hogging bending moment and local bending at T-section. This mode of behaviour is different from that at failure of the unrestrained beam. This is confirmed by Fig. 7 where plastic yield of the top T-section around the opening of the axially restrained beam is clearly shown. At the same temperature, the unrestrained beam has only a

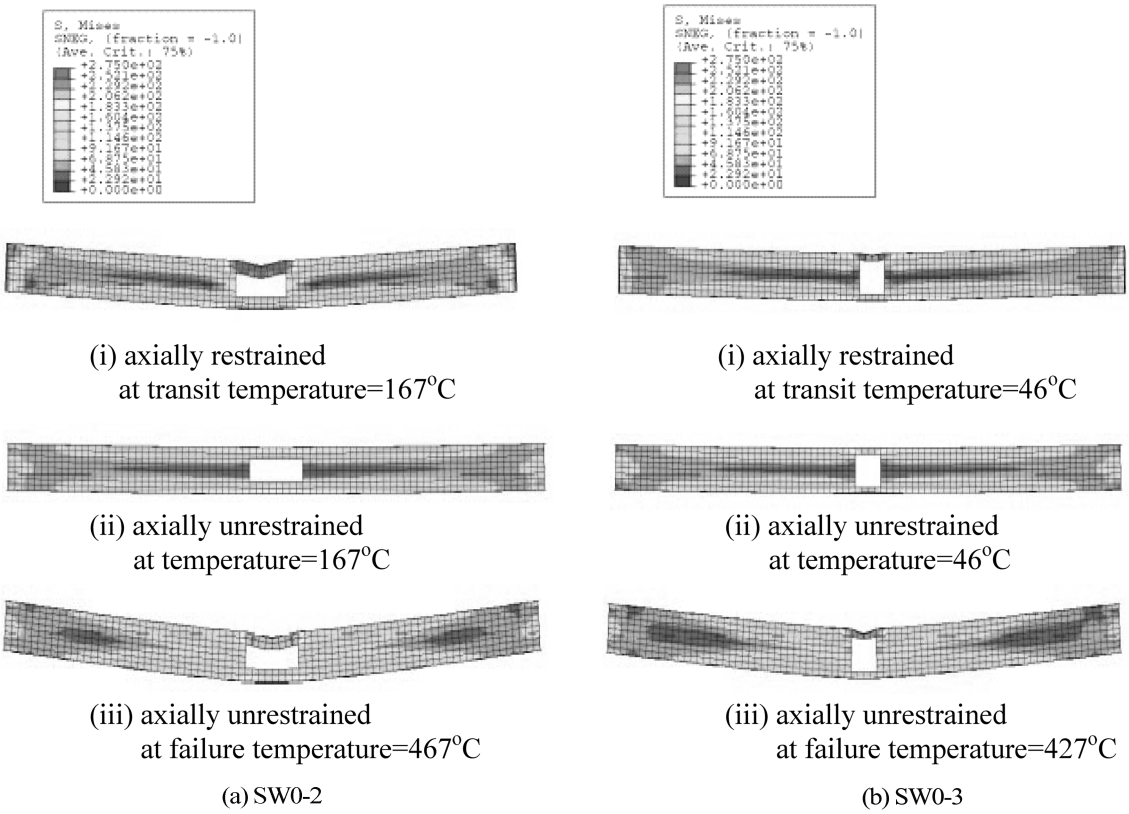
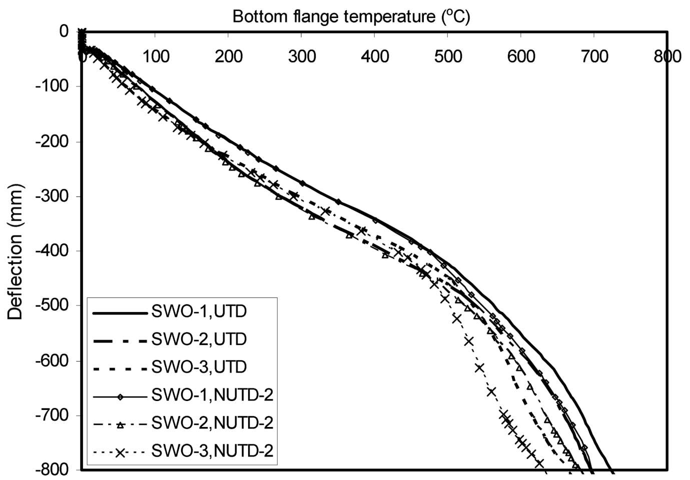


Fig. 7 Stress distribution for beams with a single web opening under uniform temperature distribution

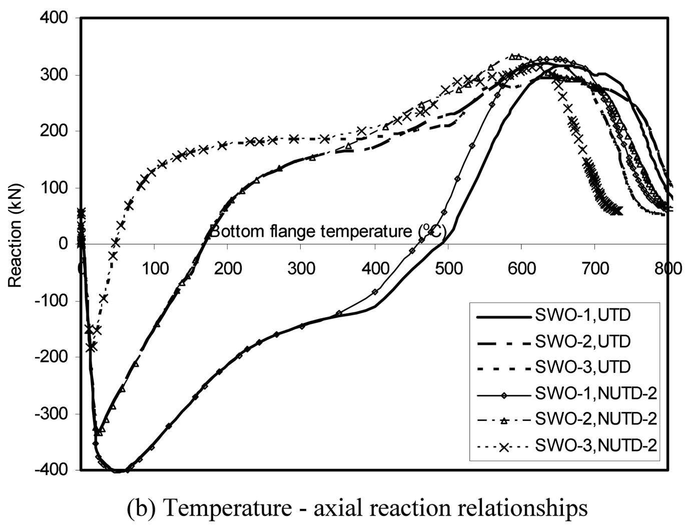
very low level of stress. This difference depends on the opening size, with the effect of deep opening being greater than that of a wide opening. Thus, the transit temperature is the lowest for opening SWO-3, followed by SWO-2, then SWO-1.

Because beams are usually designed as unrestrained, this is an important observation. This research shows that for beams with web opening, the transit temperature of a restrained beam can be much lower than the failure temperature of the unrestrained beam. If the connections and columns to the beam have not be designed to resist tension forces, there could be a danger that an axially restrained beam could induce collapse before reaching the failure temperature of the unrestrained beam, implying that the assumption of an unrestrained beam is not necessarily safe.

Fig. 8 further compares the behaviour of beams with a single web opening under uniform temperature distribution UTD and non-uniform temperature distribution NUTD-2. At large deflections, the



(a) Temperature - deflection relationships



(b) Temperature - axial reaction relationships

Fig. 8 Comparison of the behaviour of beams with different single web opening, full axial restraint, different temperature distributions difference in beam behaviour under UTD and NUTD-2 is very small. For simplicity, uniform temperature distribution can be assumed.

3.2. Results for beams with multiple web openings

The dimensions and positions of openings in beams with multiple web openings are shown in Fig. 9. MWO-1, MWO-2 and MWO-4 have two openings of the same size, but at different locations. MWO-3

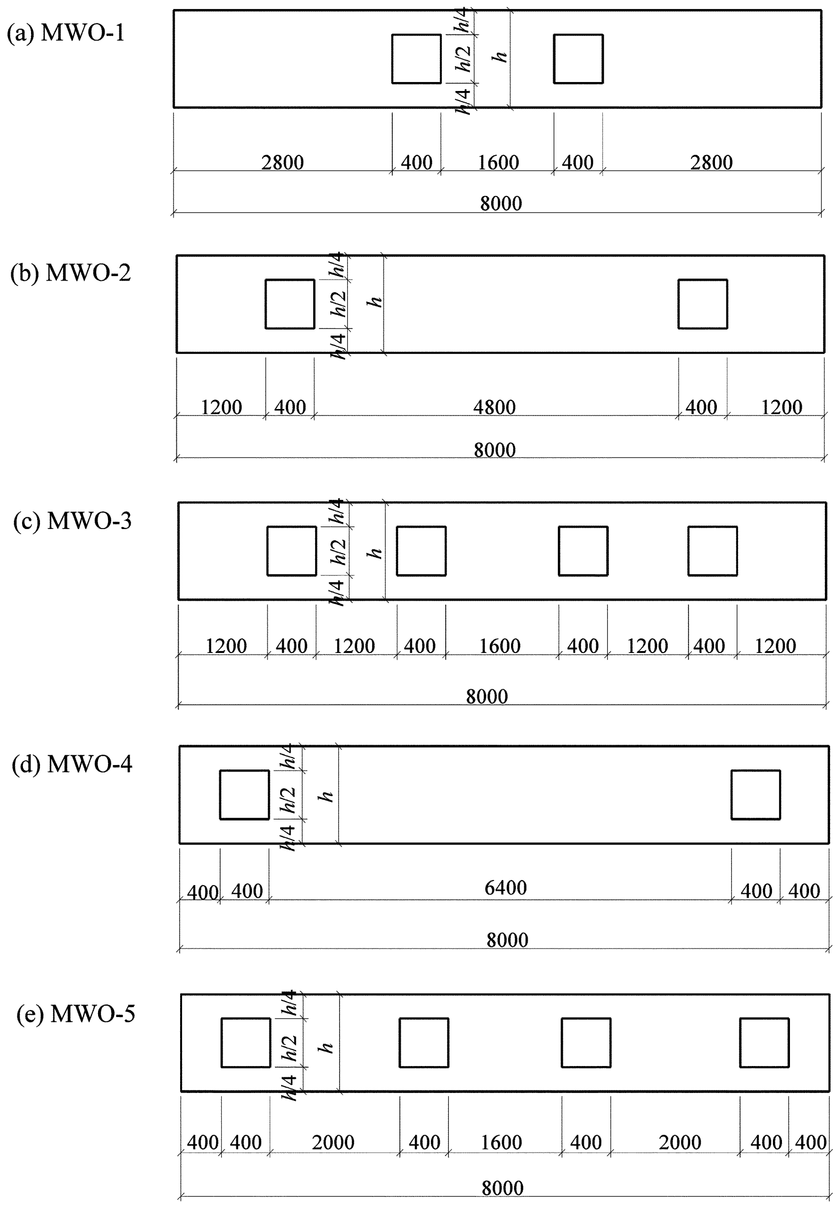


Fig. 9 Dimensions of beams with multiple web openings

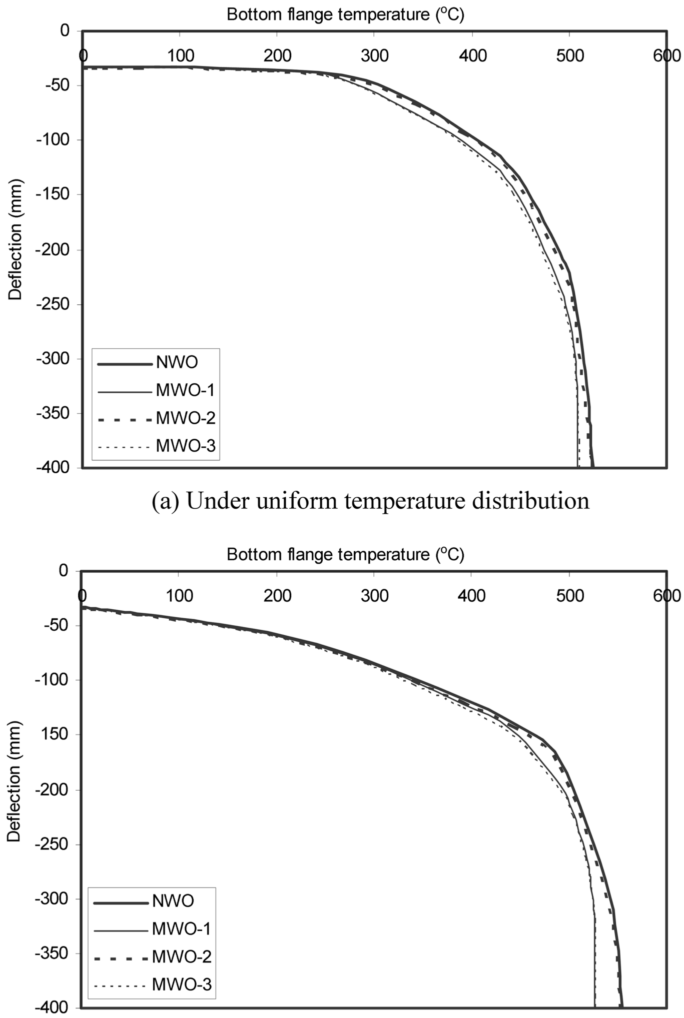
has four openings, combining openings of both MWO-1 and MWO-2. MWO-5 has four openings, combining openings of both MWO-1 and MWO-4.

3.2.1. No axial restraint

Fig. 10 compares the beam temperature - deflection relationships.

Because the opening size is relatively small and no opening is at the critical section of the beam, i.e., centre, Fig. 10 shows that the behaviour of beams with multiple web openings is similar to that without opening. In particular, because the openings of MWO-2 are far away from the beam centre, the behaviour of beams with NWO and MWO-2 are almost identical, so are those with MWO-1 and MWO-3.

The identical behaviour of MWO-1 and MWO-3 beams indicates that for beams with uniformly



(a) Under uniform temperature distribution

(b) Under non-uniform temperature distribution NUTD-1

Fig. 10 Comparison of the behaviour of beams without and with multiple web openings, no axial restraint distributed loads, no matter how many openings are present, it is the web opening at the critical position that largely governs the beam's behaviour.

3.2.2. Full axial restraint

The same exercise as for beams with a single web opening has been performed for beams with multiple web openings. Figs. 11~12 compare the beam temperature - deflection and temperature - axial reaction relationships.

It can be seen from the figures that at lower temperatures, the beam's deflection and compression force depend on the position of the web opening in the beam. Since the opening size is small in this case, local bending at T-section has no obvious effect on the beam behaviour, thus at this stage, there is strong interaction between bending moment and axial force. Beams with multiple web openings,

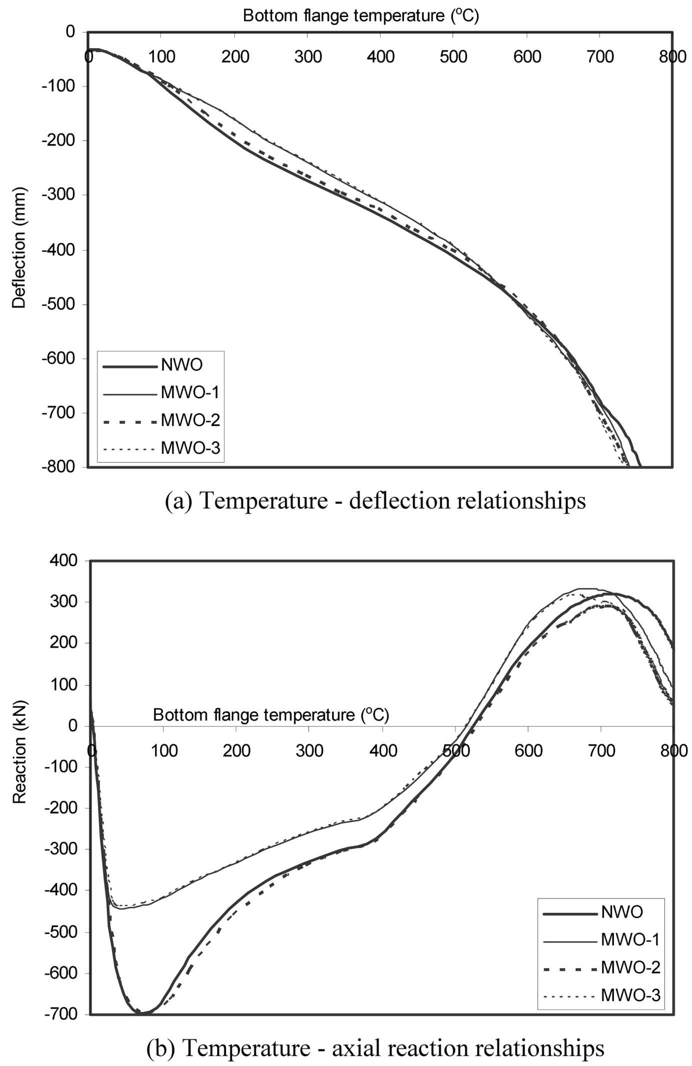
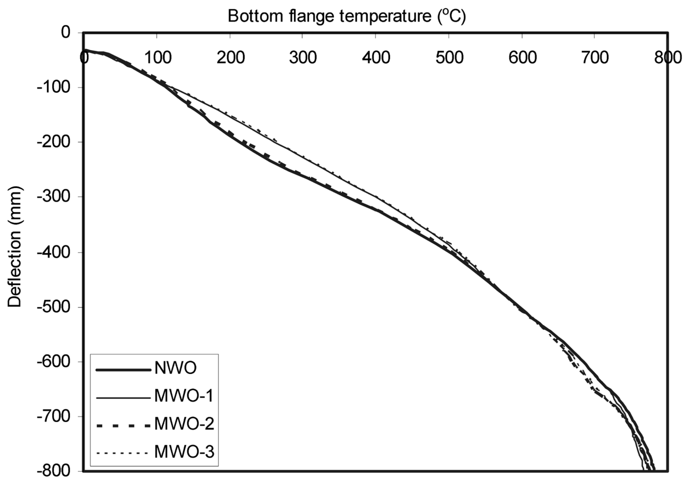
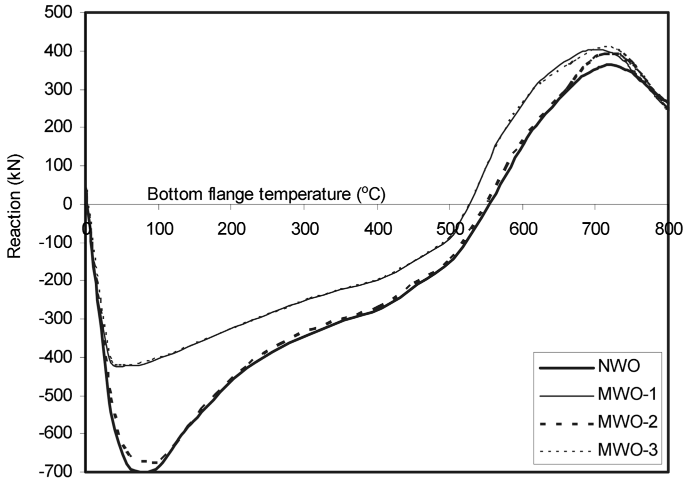


Fig. 11 Comparison of the behaviour of beams without and with multiple web openings, full axial restraint, uniform temperature distribution



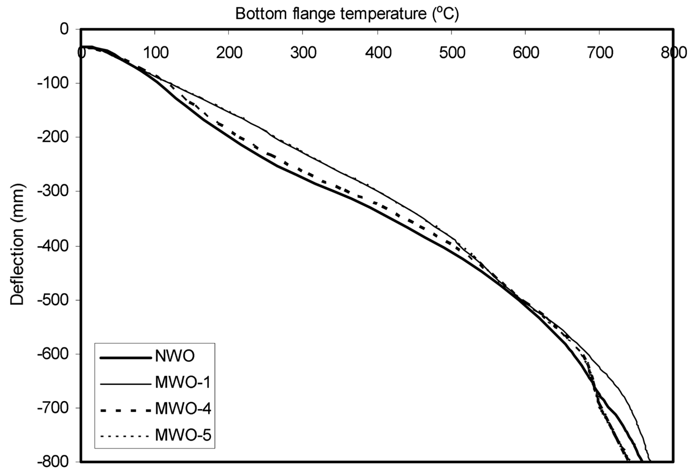
(a) Temperature - deflection relationships



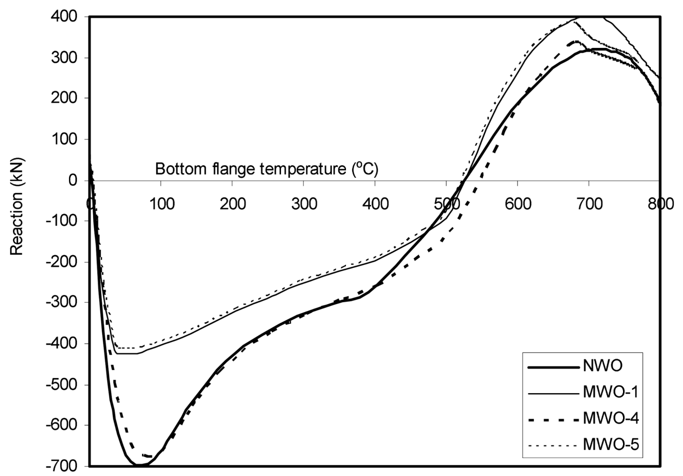
(b) Temperature - axial reaction relationships

Fig. 12 Comparison of the behaviour of beams without and with multiple web openings, full axial restraint, non-uniform temperature distribution NUTD-1

MWO-1 and MWO-3 have their openings at locations of relatively high bending moment, so that they do not have high resistance in compression. However, at higher temperatures, catenary action takes over and the effect of bending moment resistance is small. Thus at this stage, it is the opening size, not number or location of openings, that determines the beams large deflection behaviour. In this analysis, the three beams have the same opening size and thus the same axial capacity. It follows that their deflections and catenary forces at high temperatures are very similar. Also since the reduction in the beam cross-section size is small, their behaviour is close to that of the beam without web opening. This is confirmed by Fig. 13 which shows the behaviour of beams with openings near the beam ends.



(a) Temperature - deflection relationships

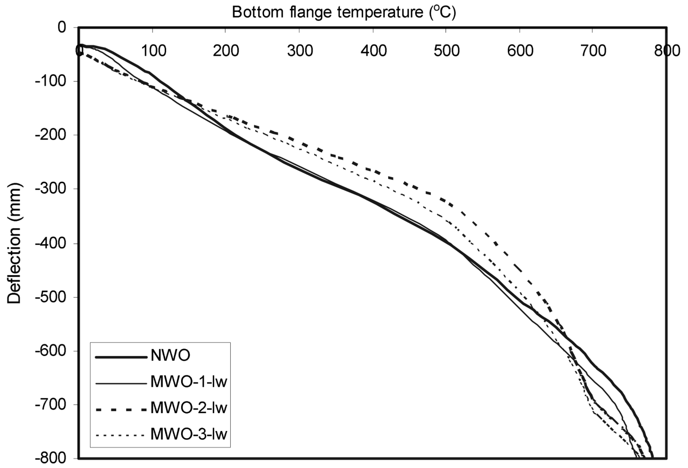


(b) Temperature - axial reaction relationships

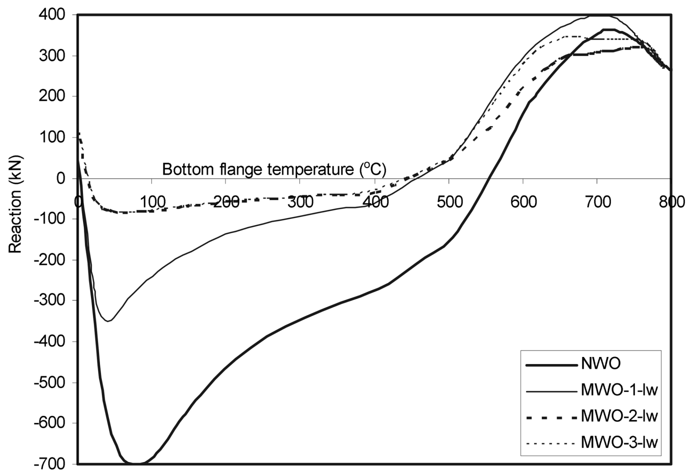
Fig. 13 Comparison of the behaviour of beams without and with multiple web openings (openings near beam ends), full axial restraint, non-uniform temperature distribution NUTD-1

Further analysis has been carried out for beams with multiple web openings of large opening width or opening depth under non-uniform temperature distribution NUTD-1, which is shown in Figs. 14~15. In Fig. 14, MWO-1-lw, MWO-2-lw and MWO-3-lw represent beams with multiple web openings at the same position as MWO-1, MWO-2 and MWO-3 shown in Fig. 9, but the opening width is doubled. Similarly, in Fig. 15, MWO-1-ld, MWO-2-ld and MWO-3-ld represent beams with opening depth 3/2 of that of MWO-1, MWO-2 and MWO-3 respectively.

From Figs. 14~15, it is confirmed that at lower temperatures, the beam's deflection and compression force depend on the position of the web opening in the beam. For a beam with openings of large width or depth, it is the local bending at T-section that controls the beam behaviour, a beam with openings near to the ends with large shear force (MWO-2-lw, MWO-2-ld) are more critical than that with



(a) Temperature - deflection relationships

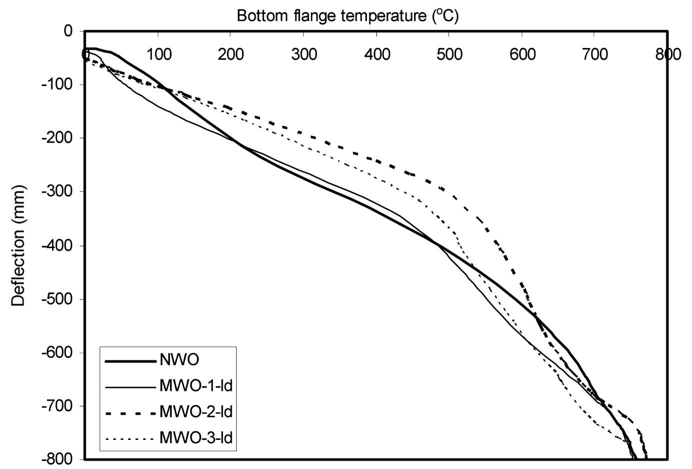


(b) Temperature - axial reaction relationships

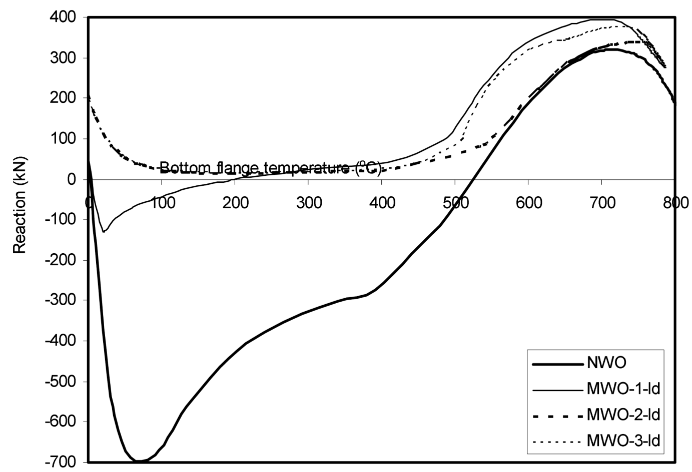
Fig. 14 Comparison of the behaviour of beams without and with multiple web openings of large opening width, full axial restraint, non-uniform temperature distribution NUTD-1

openings close to the middle of the beam (MWO-1-lw, MWO-1-ld), thus it has lower compression force and develops into tension at a lower temperature. Figs. 14~15 also show that the behaviour of MWO-2-lw and MWO-3-lw, MWO-2-ld and MWO-3-ld are very similar, therefore confirmed that for axially restrained beams, at lower temperatures, it is the openings at the critical position that govern the beam behaviour.

Comparing Figs. 12, 14 and 15, it shows that opening size only has some small effects on the large deflection behaviour of axially restrained beams at higher temperatures. But it will significantly affect the transit temperature when the beam develops into catenary action, with beams with large opening depth having the lowest transit temperature, followed by beams with large opening width.



(a) Temperature - deflection relationships



(b) Temperature - axial reaction relationships

Fig. 15 Comparison of the behaviour of beams without and with multiple web openings of large opening depth, full axial restraint, non-uniform temperature distribution NUTD-1

4. Conclusions

This paper has presented a brief analysis of the behaviour of steel beams with web openings at elevated temperatures. It can be concluded that:

- For an axially unrestrained beam, the presence of web openings will not change the deflection mode of the beam, but the size and position of the opening will affect its failure temperature. For beams with multiple openings, it is the opening at the critical position that determines the whole beam behaviour.
- For an axially restrained beam, the beam's deflections and compression forces at lower temperatures depend on the opening size at the critical position in the beam. At higher temperatures,

the present of web openings will have some effect on the beam's large deflections and catenary forces, but the influence is relatively small compared to beams without axial restraint.

- It is possible that catenary action develops in beams with web opening at temperatures much lower than the failure temperatures of unrestrained beams that are often used as the basis of current design. This raises the issue that should the connections to the beams with web openings not have sufficient resistance to the catenary forces, the connections could fracture, thus leading to failure in the structure before the failure temperature of the unrestrained beams.
- Non-uniform temperature distribution will affect the behaviour of beams with web openings. The higher the contribution of the upper part to the beam's overall capacity, the smaller the difference between the behaviour of the beams with and without web openings.
- For axially restrained beams, the beam behaviour is insensitive to the high temperatures around the openings. But for beams without axial restraint, the reduction of failure temperatures as a result of high temperature around the opening will become noticeable when the opening size becomes larger.

The current analysis of perforated beams at elevated temperatures is not very comprehensive. It has only considered rectangular web openings and a small number of opening depths, widths and positions. This does not cover the entire range of bending moment - shear force interaction relationship at T-section. Before comprehensive conclusions can be drawn, further research studies regarding different opening sizes, shapes, positions and characteristics of beam end restraints will be necessary. Also thermal analysis would be required to provide more comprehensive information on the exact temperature distribution in the cross-section of beams with web openings.

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