Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

DESIGN OF STEEL I-BEAMS WITH WEB OPENINGS

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The paper presents a numerical research on the behavior of steel I-beams with web openings. The influence of web openings in the load carrying capacity of steel beams and failure mechanisms are investigated. The non-linear numerical analysis performed was calibrated with results from other similar non-linear numerical analysis and experimental test data. Comparison between numerical results with the available experimental for yielding patterns, ultimate load values and load-deflection relationships show a good agreement. The numerical model developed was used to carry out a parametric study taking into account some parameters, such us: opening shape, opening size, and the location of the opening throughout the span. Three different beam spans were considered. A contribution to the analysis and selection of the web openings best solutions is presented in the conclusions.

Keywords: Shear moment interaction, Parametric analysis, Finite element method, Circular and square shapes, Load capacity, Opening sizes.

1 INTRODUCTION

In modern buildings there is always a need to integrate building services within floor zones. A common method of integrating services within the floor-ceiling zone of buildings is to create large openings in the webs of the steel I-beams. The openings are most likely to be rectangular or circular, and may be in the form of discrete openings, or a series of openings, along the steel beams.

The presence of web openings may have severe penalties on both shear and flexural capacities of beams, depending on shapes, sizes, and locations of the web openings. Thus, flexural and shear failure may be found at points of high bending moments and high shear forces along the perforated beams. Moreover, depending on the length of the web openings and the moment over shear ratios, M/V, at the centers of the web openings, the shear forces acting across the web openings produce "Vierendeel" moments which may cause local flexural failure in the top and the bottom tee sections above and below the web openings.

2 SCOPE OF THE INVESTIGATION

Based on the finite element models established for steel beams with circular web openings, a comprehensive parametric study was carried out to investigate and compare the load carrying capacity of steel beams with web openings of various shapes, sizes, and in different positions along the beam. For three different beam spans, a total of three different opening shapes with three different sizes located in four different positions along the steel beam of two different section sizes were covered with a total of 290 non-linear finite element runs. It was envisaged that the finite element results would provide understanding on the structural behavior of the perforate sections in terms of deformation characteristics, moment shear interaction curves and load carrying capacities at failure. In the present study, all steel beams are hot rolled steel I and H sections of class 1 or 2 (plastic or compact). All web openings are concentric to the mid-height of the sections with sizes between 0.25 h and 0.75 h, where h is the section depth; no reinforcement is considered. It should be noted that the bending moment, M_{Ed}, and the shear force, V_{Ed}, due to global actions are evaluated at the center of the web openings at failure stage.

3 PARAMETERS ANALYZED

The steel beams considered in the research were HEA800 and IPE500, european commercial steel profiles. It was adopted a bi-linear stress-strain curve with 0,0025 strain hardening, Young modulus E = 210 GPa and yield strength of 355 MPa for all sections for ease of comparison despite variation in flange thickness. The results are considered to be equally applicable to steel beams with yield strengths of 275 N/mm^2. The present research was focused on the following parameters:

- Opening shapes: Three opening shapes were considered: i) circular; ii) square; and iii) rectangular.
- Opening sizes: Three different sizes were considered: i) 0.25 h; ii) 0.50 h; and iii) 0.75 h, where h is the section height of steel beam.
- Opening position along the beam span: Four different locations were considered to the web openings: 0.125 L, 0.25 L, 0.375 L, and 0.50 L from the support, where L is the beam span.

4 FINITE ELEMENT MODELS

In order to numerically simulate the structural behavior of steel beams under practical loading and support conditions, 3D finite element models were established using the general purpose finite element package ADINA, version 8.7.3 (2011). To avoid discontinuities in stress contours across element boundaries, it was used a refined mesh configuration in the vicinity of the web opening. The finite element models used in the parametric study were calibrated against some results from similar models presented in the work of Chung *et al.* (2001, 2003) and Liu *et al*. (2003) and test results reported by Redwood and McCutcheon (1968).

5 RESULTS OF THE PARAMETRIC STUDY

A total of 290 non-linear finite element runs were performed, Bernardino (2013), covering different opening configurations and sizes, located in different positions along the steel I-beam spans, for different beams sizes (HEA800 and IPE500) and beam spans (4.0 m, 6.0 m, and 10.0 m spans). All beams are simply supported and under uniformly distributed loads.

5.1 Load-Deflection Curves

Load-deflection curves of HEA800 beams with web openings of various shapes and sizes are plotted in Figure 1. In general terms four different zones can be observed in the curves: initial linear elastic deformation, non-linear deformation, ultimate stage near failure and failure with unloading.

The effect of opening shape and size on the behavior of the beam is also illustrated in the figure. Curves corresponding to larger openings are less stiff even from the lower loads and also exhibit significant drop in the ultimate load for the larger openings.

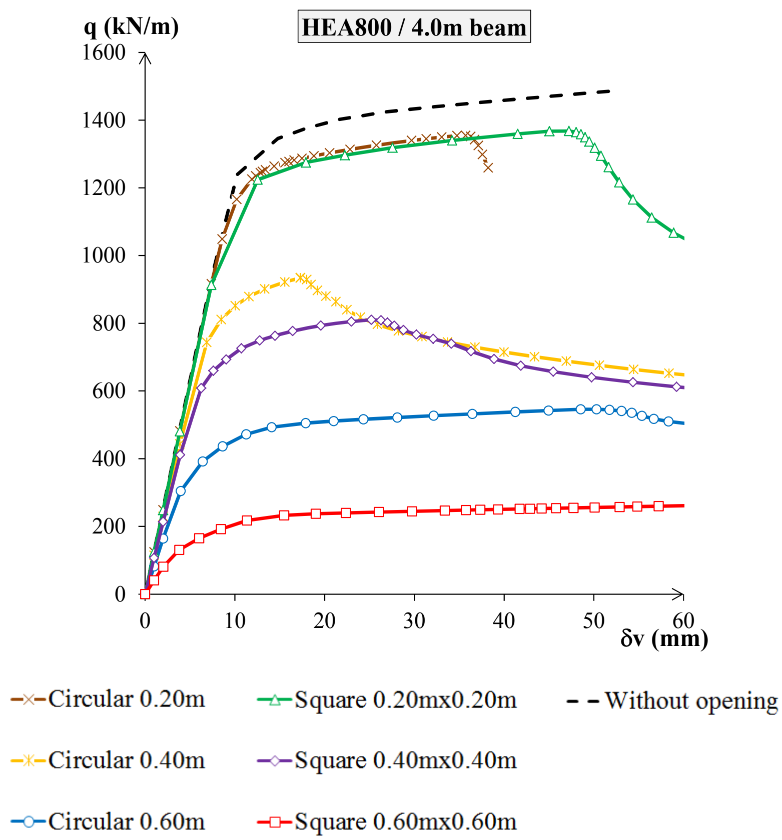

Figure 1. Load-deflection curves of perforated sections at 0.125 L.

5.2 Moment-Shear Interaction Curves

Moment-shear interaction curves obtained from the finite element investigation are presented in Figures 2 and 3. It should be noted that the global shear force V_{Ed} and the global moment M_{Ed} at the center-line of the perforated sections correspond to the failure stage.

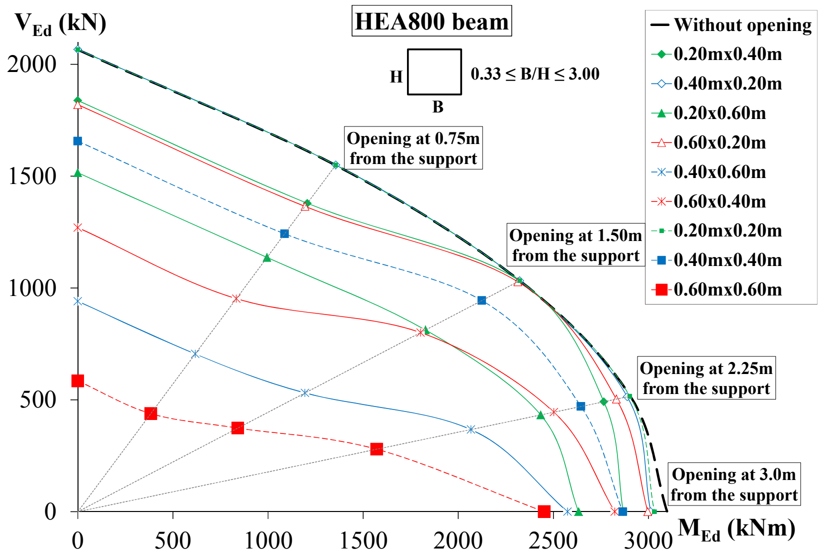

Figure 2. Moment-shear interaction curves of perforated sections (square/rectangular) at failure in 6.0 m span of HEA800 beams.

The moment-shear interaction curves obtained for different spans show that the reduction of the load carrying capacity is higher near the support for small span ($L_{span} \leq$ 6.0 m) and higher near the mid-span for longer span ($L_{span} >$ 6.0 m). These curves also show that for openings with the same size, the influence of the web opening geometry is smaller near the mid-span. The load carrying capacity of the beam is almost the same for openings with the same height, independent of the length of the opening.

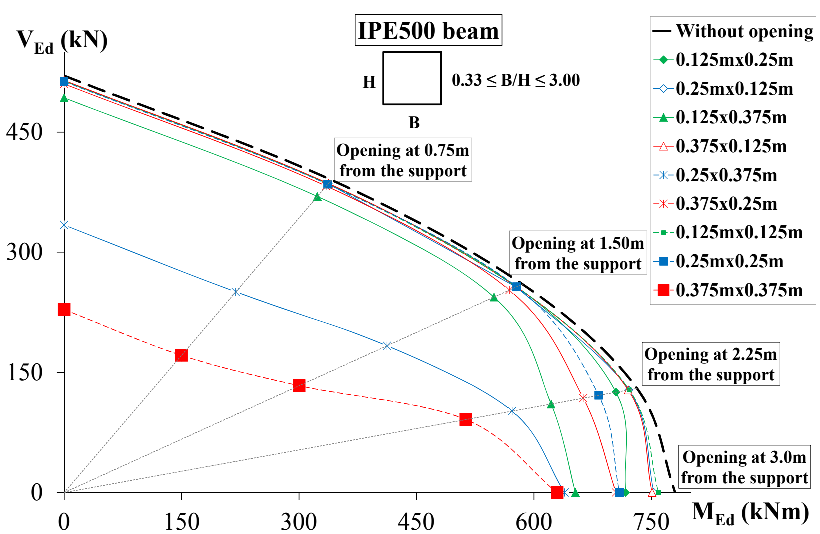

Figure 3. Moment-shear interaction curves of perforated sections (square/rectangular) at failure in 6.0 m span of IPE500 beams.

5.3 Load Carrying Capacity

In Figures 4 and 5 are plotted load carrying capacity curves, q_{max}, of simply supported beams for some of the evaluated cases.

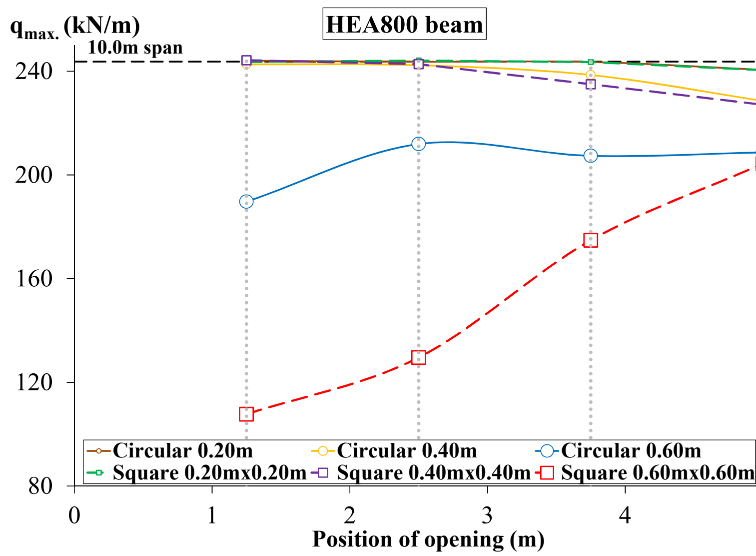

Figure 4. Load capacity vs opening position (Circular and square).

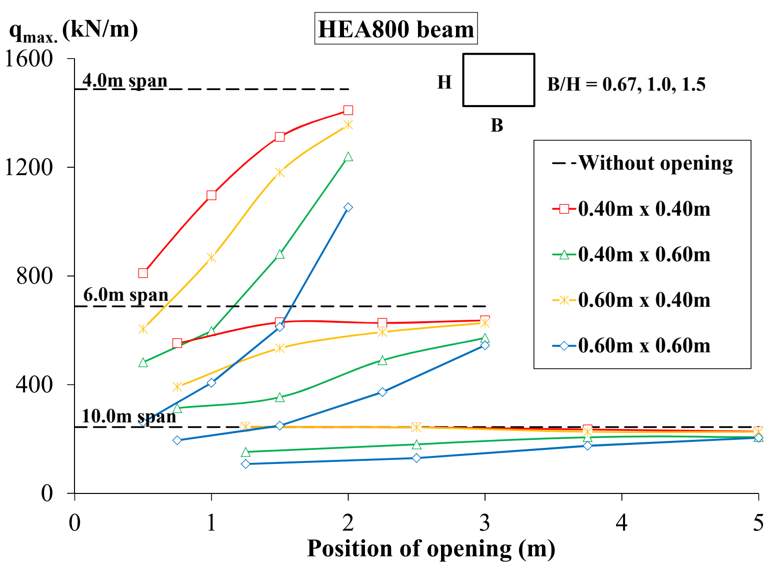

Figure 5. Load capacity vs opening position (Rectangular and square).

For all spans studied and openings size equal or greater than 0.50 h, it is observed that the load carrying capacity of steel beams with circular web openings is higher than the load carrying capacity of steel beams with square web openings. The reduction of the load carrying capacity of steel beams vs web opening position along the beam span is greater for small spans. This reduction decreases as the beam span increases. Also, there is a significant reduction of the load carrying capacity of steel beams with larger web openings near the supports. The influence of the web opening height in the reduction of the load carrying capacity of steel beams is more important than the length of the opening, for any span and position of the opening along the beam span.

6 CONCLUSIONS

As a result of the parametric study, some qualitative recommendations can be made:

- For all spans studied and for web opening sizes $B > 0.50H$, it is observed that the load carrying capacity of steel I-beams with circular web openings is higher than the load carrying capacity of steel beams with square web openings.
- For beams with spans $L > 6.0$ m, when the opening is located at mid-span, and for the same opening height, it is possible to increase the length of the opening to a maximum of 0.75H without a decrease of the beam load carrying capacity.
- For beams spans $L > 10.0$ m, and for web openings size equal or smaller than 0.50 h, the openings should be located between the supports and one quarter of the span.
- For beam with spans $L > 10.0$ m, and for web opening ratio $B/H > 0.5$ and $B/H < 2.0$, the opening can be located between the supports and one quarter of the beam span.

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