Analysis and Design of Composite Beams with Web Openings

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Abstract

This paper provides guidance on determining the design resistance of composite beams with large web openings.

A numerical model has been developed, in order to evaluate the structural behaviour of perforated beams as well as the influence of web openings in the load carry capacity. The non-linear behaviour of the concrete and steel has been taken into account. Thus, the concrete has been modelled with concrete damaged plasticity, CDP, included in the finite element software. The model's calibration and validation based in experimental tests and numerical models published, guaranteed that the modelled materials and simplifications made in the model would provide to the desirable results.

The behaviour of beams with large web openings is described and a design model is presented. Expressions are given for the design resistances of the Tee sections above and below openings, all generally following the principles and terminology of Eurocodes 2, 3 and 4.

Finally, the last part of the research consists in the demonstration and discusses of the parametric study results made from a numerical model.

Keywords: Composite beam; Perforated section; Web opening; Vierendeel mechanism; Shear moment interaction curves; Concrete damaged plasticity;

1. Introduction

Composite beams comprise steel I-sections or H-sections attached by shear connectors to a concrete or composite slab, so that the bending resistance and flexural stiffness of the beams are considerably higher than those of steel section alone. A common method of incorporating services within the floor-ceiling zone buildings using this form of construction is to create large openings in the webs of I-sections or H-sections 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 beam. Two examples are shown in Figs. 1 and 2.

The presence of web openings may have a severe penalty on the load carrying capacities of beams, depending on the shapes, the sizes and the locations of the web openings. Due to the presence of web openings, three different modes of failure may take place at the perforated sections as follows:

i) Shear failure;
ii) Flexural failure;
iii) Vierendeel mechanism.

A large number of tests has been carried out on composite beams with discrete rectangular openings, notably those at the University of Kansas, USA [1,2], and also in Canada [3] and at the University of Kaiserslautern, Germany [4].

Fig. 1 Cellular beam with a series of circular openings.

Fig. 2 Rectangular web openings in composite beams.

2. Behaviour of composite beams with web openings

The forces acting around a rectangular opening in the web of a composite beam are shown in Fig. 3. The global bending action is resisted by tensile force in the lower Tee section, and by compression force in the concrete slab, which is controlled by the longitudinal shear forces developed in the shear connectors is limited, and therefore compression force is also developed in the upper Tee section (as in partial shear connection).

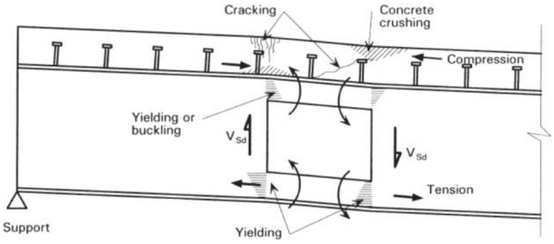


Fig. 3 Forces around an opening in a composite beam.

In general, the shear force at an opening is mainly resisted by the web of the upper Tee section, because the lower Tee section is often highly stressed in tension. The concrete slab also participates in resisting this shear force [5,6].

Local Vierendeel bending action occurs due to the rate of change of bending moment, hence the shear force, across an opening. This increase in bending moment is resisted by the local bending resistances of the upper and lower Tee sections. At the higher moment side of the opening, composite action occurs between the upper web-flange section and the concrete slab. The magnitude of this tension-compression couple depends on the number of shear connectors provided directly above the opening. In general, this local composite action dramatically improves the resistance of the composite beam against the Vierendeel bending, and therefore longer openings can be used in composite beams than in steel beams [7].

The bending resistance of a composite beam subject to these forces is illustrated in Fig. 4. For structural adequacy, the total Vierendeel bending resistance of the Tee sections incorporating local composite action at an opening, should exceed the design shear force times the effective length of the opening, $V_{Sd}l$.

The optimum positions for web openings in the span of the beam depend on the relative proportion of bending moment and shear forces. In general, the openings have a greater effect on the shear resistance of the beam than the bending resistance [7]. Thus, the optimum positions for large openings tends to be roughly at the quarter span points of a uniformly loaded beam, where the shear force is 50%, and the bending moment is 75% of their maximum values.

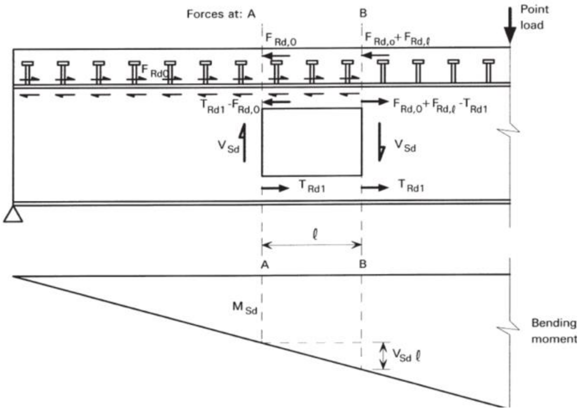


Fig. 4 Global and local bending resistance due to composite action.

3. Analytical design approach for beams with single web openings

An overall review on the design recommendations [6–9] shows that in general, there are two design approaches in assessing the structural behaviour of beams with rectangular web openings.

3.1. Tee section approach

In this approach the structural adequacy of a bema with web openings depends on the section resistances of the tee sections above and below the web openings under co-existing axial forces N_T, shear forces V_T and local moments M_T, as shown in Fig. 5. All of these local forces and moments are due to global bending action. The accuracy of the design methods depends on the accuracy of a number of design rules against respective failure modes. Moreover, there are a number of different ways in allowing for the effects of co-existing axial and shear forces in assessing the moment resistances of tee sections. The calculation procedures are usually complicated and they differ significantly among each other, depending on the design methodology adopted, and also the calculation efforts involved. It should be noted that the design methods are often very general, and applicable in principle for beams with web openings of various shapes and sizes. However, due to the complexity of the problems, approximate design rules are often presented for practical design to reduce calculation effort, leading to conservative results.

3.2. Perforated section approach

In this approach, the perforated cross-sections are the critical sections to be considered in design. The structural adequacy of the beams depends on the section resistances of the perforated sections under co-existing global shear force, V_{Ed}, and bending moment, M_{Ed}. In general, the design procedures for both the shear and the moment resistances of perforated sections are relatively simple and similar among different methods. However, the Vierendeel moment resistances of the perforated sections are evaluated implicitly based on various assumptions on the effects of co-existing shear forces and moments. Simplifications are usually made to those design rules derived from the Tee section approach, and thus, empirical global shear-moment (V-M) interaction curves are often provided to engineers for practical design. However, it is the simplification or the over-development on the design rules that reduces the scope of applicability of the design rules.

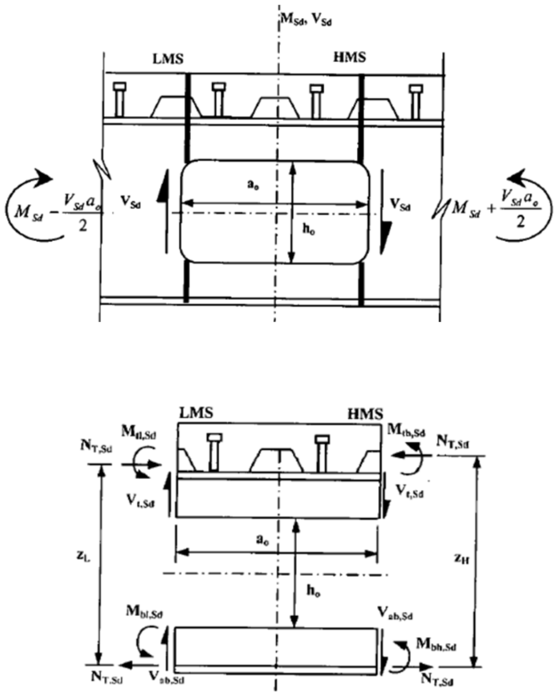


Fig. 5 Global and local actions at perforated section of a composite beam.

4. Finite element modeling

In order to verify the structural behaviour of composite beams with large web openings, a finite element model is established. Comparison on the predicted ultimate loads of four composite beams from the finite element models and the test data acquired is presented.

The general purpose finite element package ABAQUS was adopted for the numerical simulation of composite beams with large web openings. Despite the principal mode of failure involves only in-plane deformation, a three-dimensional finite element model is adopted with the following features:

- Iso-parametric eight-node with reduced integration elements (C3D8R) are used to model both the concrete slab and the steel beam.
- A bi-linear stress-strain curve is adopted in the material model of steel as shown in Fig. 6. The concrete modelling is based in concrete damaged plasticity implemented in ABAQUS. The concrete damage plasticity model uses the concept of isotropic damaged elasticity, in combination with isotropic tensile and compressive plasticity, to represent the inelastic behaviour of concrete. The constitutive relationship of concrete is presented in Figs. 7 and 8, as suggested by EN1992-1-1 [10]. It should be noted that for concrete under compression, the response is linear until the value of the proportional limit stress, f_{c0}, is reached, which is assumed to be equal to 0,4 times the compressive strength, f_c.
- With geometric non-linearity incorporated into the finite element model, large deformation in the perforated section after yielding is predicted accurately to allow for load re-distribution within the perforated section.

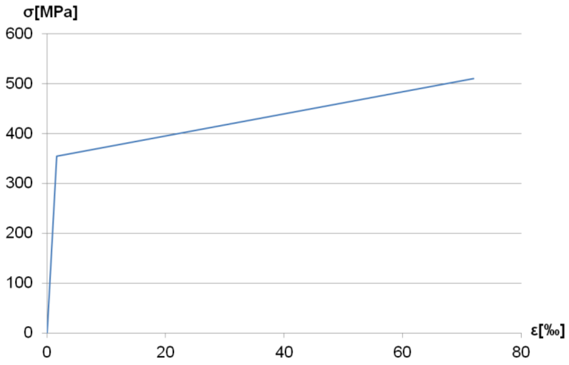


Fig. 6 Constitutive relationship of steel.

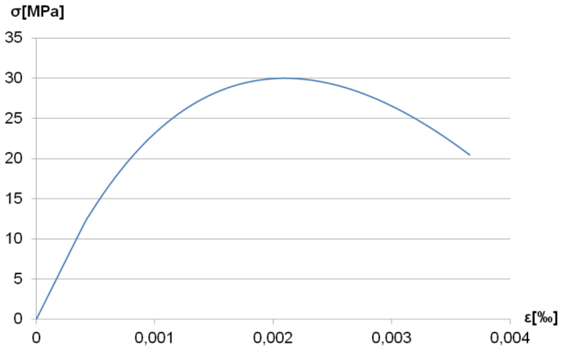


Fig. 7 Constitutive relationship of concrete in compression.

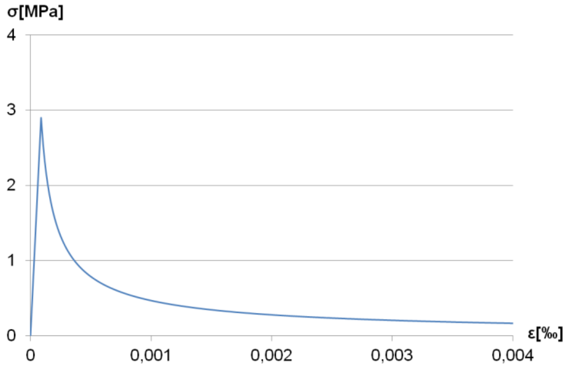


Fig. 8 Constitutive relationship of concrete in tension.

5. Calibration against experimental tests and numerical analyses

The finite element model was calibrated against data from three tests and a numerical analysis. The first comparison was established to show the response of composite beam materials, concrete and steel. Therefore, the first model developed is a conventional composite beam, as shown in Fig. 9.

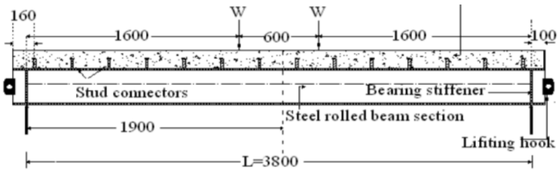


Fig. 9 Details of test specimen [13]

Prakash et al. 2011, modelled the interaction between concrete and steel with shear connectors distributed through the beam span. However, in this case the tie function is adopted to simulate the connector’s action. The main difference associated to the tie connection consists in the union of shared nodes of the different materials. The second test was a composite beam with a web opening which was conducted by Clawson and Darwin 1980, namely Test CD4. The general test set-ups and the dimensions of the test specimen are shown in Fig. 10.

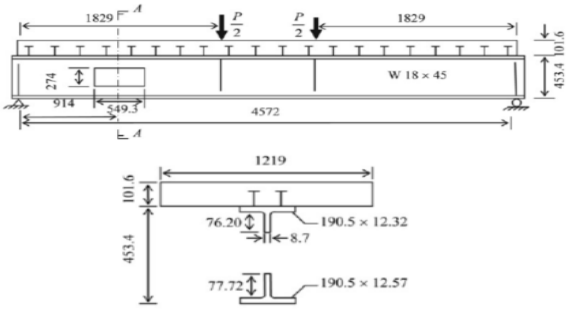


Fig. 10 Details of test specimen [9].

Moreover, the predicted load deflection curves of the composite beams are plotted in Fig. 11.It is shown that both the deformation characteristics and the ultimate loads obtained from the finite element models and the experiments agree well with one another.

The third and fourth test presented two-span [11] and three-span [12] continuous composite beams respectively. In these studies, the concrete will be both in compression and tension. The aim of these models was to show that the concrete in tension presented over the support, does not influence the resistance of the beam nor the rotation capacity.

From the results presented in the Fig. 12 and 13, it can be concluded that in case of total connection, it is good to simulate the interaction between the materials based on the tie function. It should be noted that in these models the reinforcements in the concrete slab were not modelled, since the tension capacity of concrete was considered. In both Figures, deflexion measurements were taken at midspan. The deflexion history of the continuous two and three span beam is shown in Fig. 12 and 13 respectively.

In general, the predicted load deflection curves derived from the numerical studies compare very well with the experimental data. It should be noted that in Fig. 12 the load deflection curve of the left spam is presented on the left and the right spam behaviour on the right.

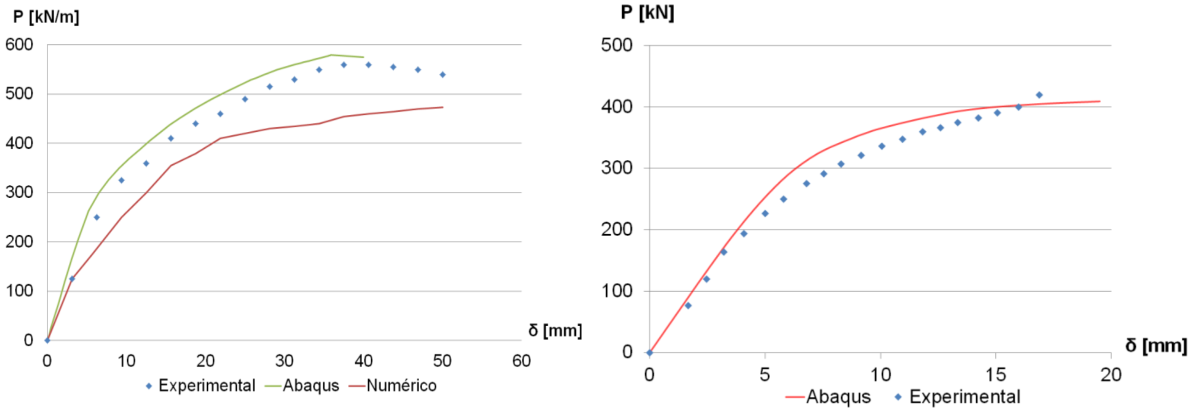


Fig. 11 Load-deflection curves, Prakash et al. 2011 to the left; Clawson and Darwin 1980, to the right

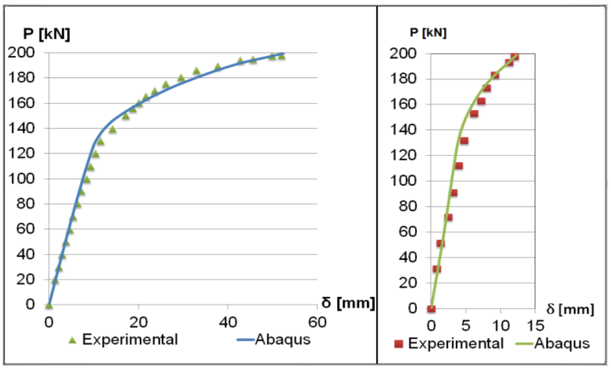


Fig. 12 Load deflection curves of the two span beam.

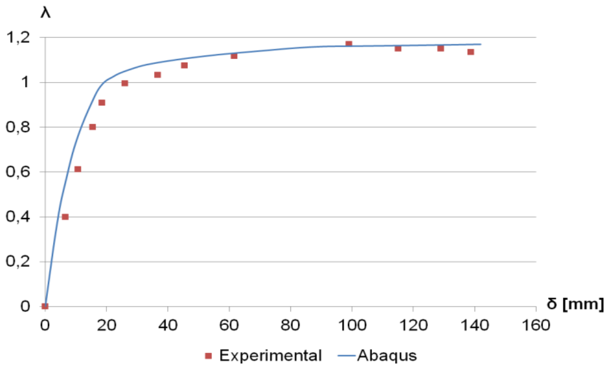


Fig. 13 Load factor-deflexion curves for centre span.

6. Parametric study

The developed model has a HEA800 or a IPE500 beam and a 250 mm thickness slab of concrete under uniformly distributed load. The width of the concrete flanges in the composite beams is taken as either the actual width or the effective width of the test beams, whichever is smaller. The effective width of the concrete flange in a composite beam is equal to a quarter of the beam span according to established design practice.

The analysis used in ABAQUS was the Static Riks, as it does iterations to obtain the ultimate load. In order to represent better the reality, the supports were modelled in a small area instead of a line with the restrictions required.

The parametric study was carried out to demonstrate the structural behaviour of composite beams with web openings. In this study was analyzed the influence of:

- The opening depth;
- The geometric configuration of the web opening;
- The location of the opening;
- The span length;
- The concrete slab thickness;
- Multiple spans.

6.1. Opening depth

It is intended that the model covers a wide range of opening depth, thus a total of three different values of opening depth are considered as follows:

- 0.25 h;
- 0.50 h;
- 0.75 h, where h is the section height of steel beam.

In order to understand the effect of the web openings size to the structural performance of perforated sections, it is important to relate the global shear force and bending moment acting on the perforated sections to the local forces and moment acting on the tee-sections above and below the web openings. It should be noted that any increase in the opening depth always reduces both the shear and the moment resistances of the perforated sections while it has no effect on the applied forces, i.e. the global shear force and bending moment at the perforated sections. Thus, both shear and flexural failures of the perforated sections are primarily controlled by the value of the opening depth.

However, while the opening length has no effect on local shear and moment resistances of the tee-sections above and below the web openings, any increase in the opening length will increase the local Vierendeel moment acting at the tee-sections significantly. Thus, the Vierendeel mechanism of the perforated sections is essentially controlled by the opening length. In practice, both the opening depth and the opening length are geometrically related, and thus any increase in sizes in web openings will reduce not only both the global shear and the global moment resistances of the perforated sections, but also the local axial, shear and moment resistances of the tee-sections- Furthermore, the Vierendeel moment is also increased at the same time.

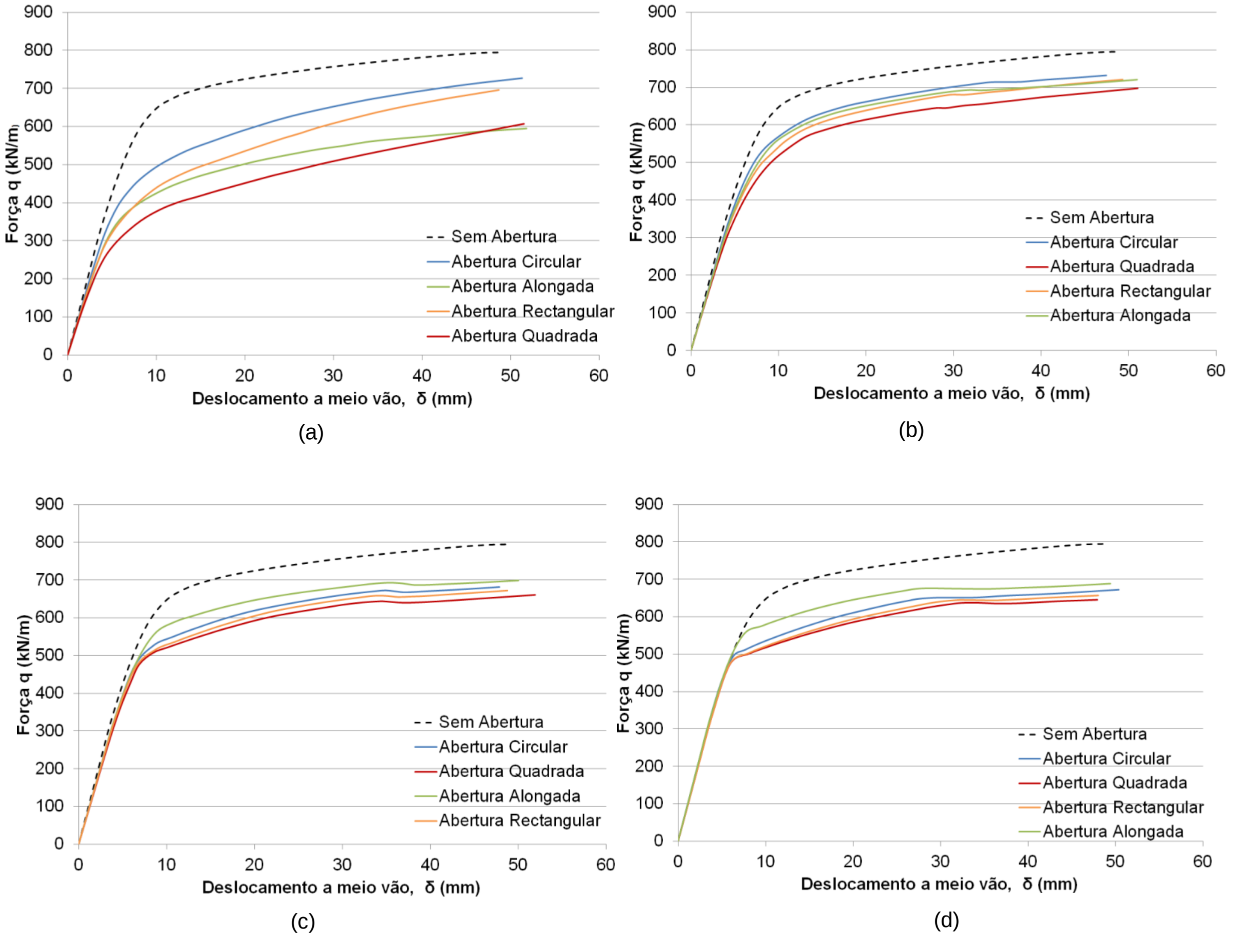
6.2. Opening shapes

A total of four web openings of different shapes are considered in the present study as follows:

- Circular;
- Rectangular;
- Square;
- Elongated circular opening.

The key dimensional parameter in all these opening shapes is the opening length, which is the length of the tee-sections above and below the openings. The length of the opening has major effect on the local applied moment on tee-sections.

For ease of comparison and discussion the results presented in this section are related to a simply supported beam IPE500 with a span of 4 m under uniformly distributed loads. It was chosen the 4 m span because the Vierendeel mechanism has a major influence in short beams. The load-deflection curves of the beams with web openings of various shapes at different locations are plotted in Fig. 14. It should be noted that for web openings of various shapes but of same opening depths and lengths, their structural performance should be similar. However, in Fig. 14 the load capacity of the beam with the square opening is not similar to the circular opening since the corners of the square opening were not rounded. It is possible to conclude that the shape is a major parameter in the structural response of the beam, however it is not possible to define a optimum shape because it depends on the opening location along the beam length. Only in Fig. 14 (a) the load-deflection curves are significantly different due to the Vierendeel mechanism.



(a)

(b)

(c)

(d)

Fig. 14 Load deflection curves of IPE500 S355 with perforated section. Openings location: (a) 0.5 m from the support; (b) 1.0 m from the support; (c) 1.5 m from the support; (d) midspan.

6.3. Location of the opening

In order to demonstrate how the location of the web openings can influence the loading capacity, an analysis was developed.

This study considers four values for the location of the web openings measured from the support to the center line of the opening:

- One eighth;
- One fourth;
- Three eighths;
- One half.

Since the Vierendeel mechanism occurs when the openings are relatively close to the support, due to the high shear force, it is expected to obtain a lower load capacity when the Vierendeel mechanism overlaps the flexural failure. It is noticeable in Fig.14 how the location influences the structural behaviour and as it was previously mentioned the optimum locations is roughly at the quarter span.

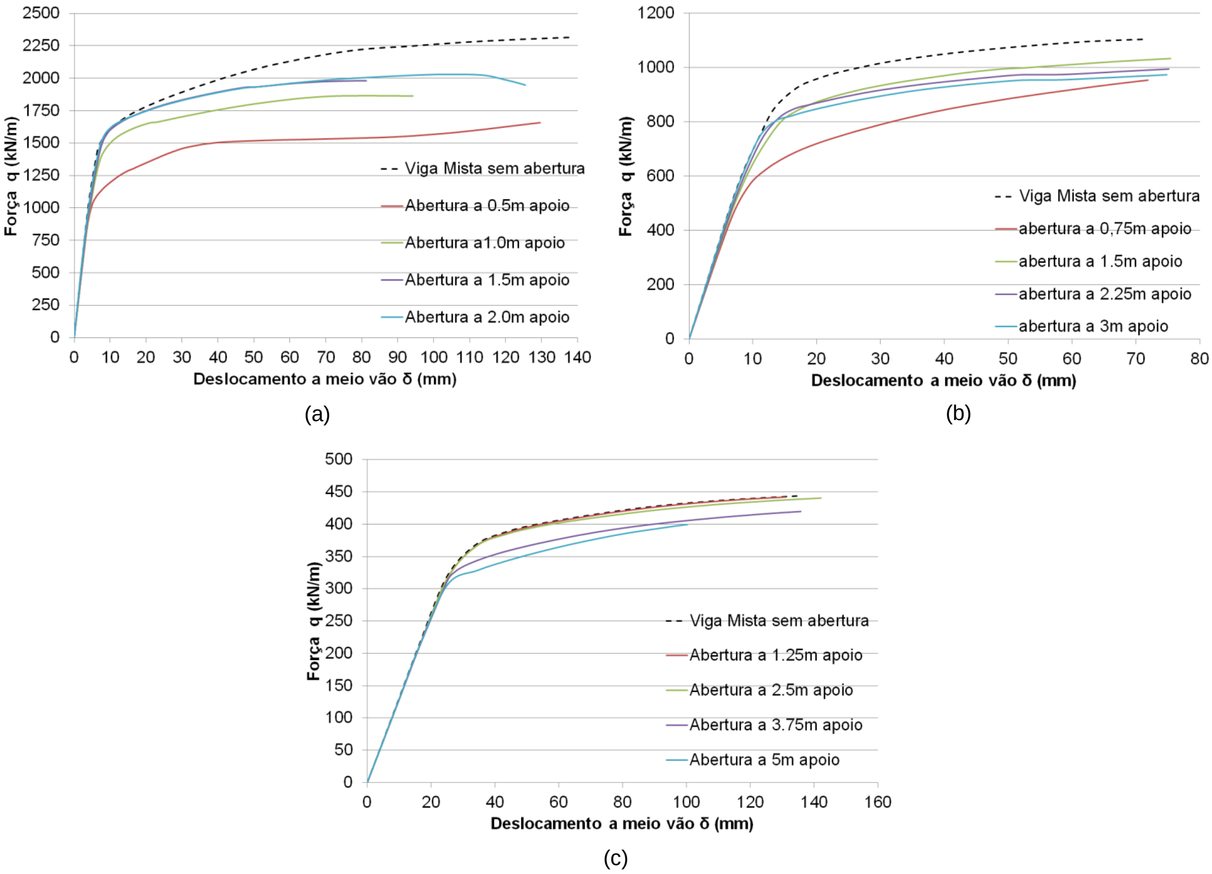
On another hand, when Vierendeel mechanism does not represent a main role in the structural behaviour, flexural failure takes place, thus the worst location for the web openings is at midspan where the bending moment is at his maximum value.

6.4. The span length

A total of four span lengths are considered in the present study as follows:

- 4.0 m;
- 6.0 m;
- 10.0 m.

Through this analysis it was found that with the increase of the span length, the Vierendeel mechanism becomes less relevant. In Fig. 15 the three spans analysed are represented, and it is possible to see that for bigger span, there is less load capacity loss due to the web openings, regardless of its position.



(a)

(b)

(c)

Fig. 15 Load deflection curves of HEA800 S355 with circular web opening, diameter 0.40 m. Span length: (a) 4 m; (b) 6 m; (c) 10 m.

6.5. Concrete slab thickness

This section is intended to demonstrate the contribution of the concrete slab in shear resistance, more specifically in resistance to bending moment of Vierendeel. The web openings reduce the shear strength capacity of the perforated section, making it susceptible to Vierendeel mechanism. In Fig. 16 and 17 is presented the Von Mises tensions in a steel beam and a composite beam with a circular opening with a diameter of 0.3 m, respectively. The concrete slab has 250 mm thickness. It should be noted that the collapse of the composite beam is a mix of Vierendeel and flexural failure, unlike the steel beam wherein failure is Vierendeel. Thus, it is possible to conclude that concrete contributes to the shear resistance of the perforated section.

6.6. Multiple spans

This study analyzes the influence of web openings in continuous beams, in other words order to determine if the existence of an opening in a span will affect the behavior of the adjacent spans.

In Fig.18, it is possible to verify that the structural behaviour of the span without the opening remains the same. It should be noted that in Figure 18 b) the load deflexion curve which has lower load capacity refers to a model in which both the spans have an opening.

It can be concluded that the existence of web openings in a certain span does not influence the load capacity of the adjacent spans.

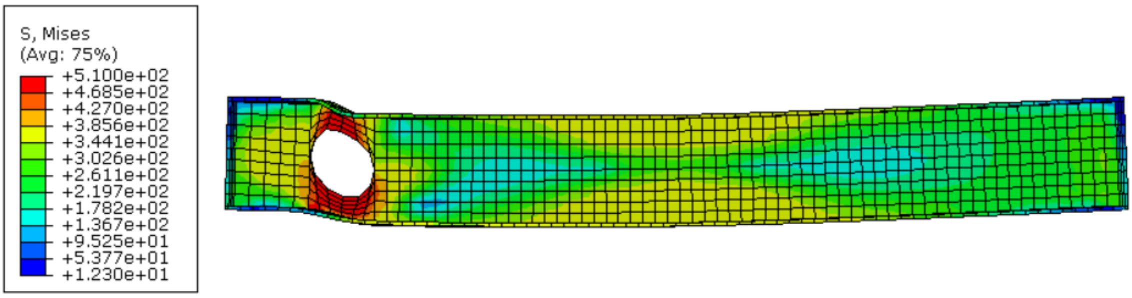


Fig. 16 Von Mises tensions in the steel beam.

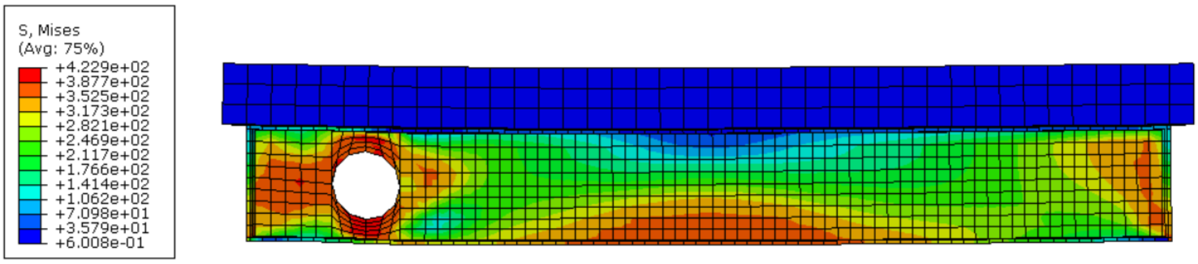


Fig. 17 Von Mises tensions in the composite beam.

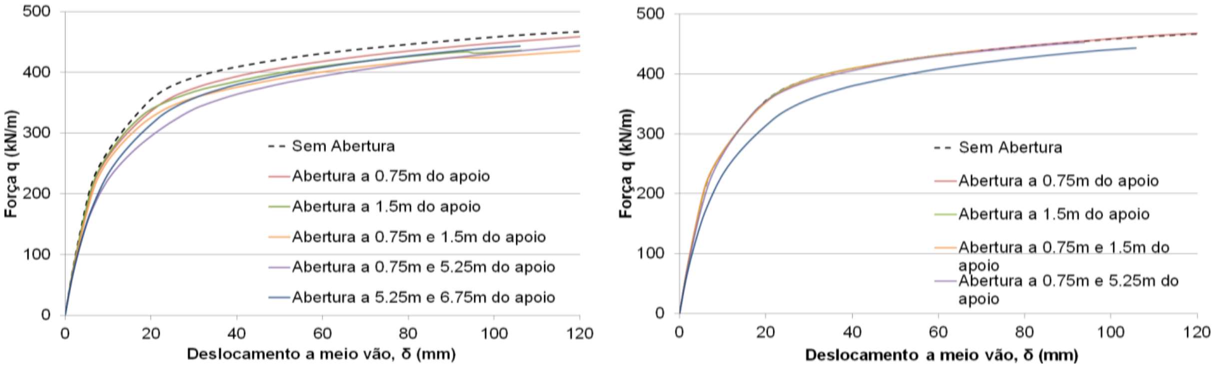


Fig. 18 Load deflection curves of IPE500 with rectangular opening. (a) Span with the opening; (b) Span without opening.

7. Conclusions

The concrete damaged plasticity failure criterions implemented in ABAQUS reveal adequate simulation of the non-linear behaviour of concrete.

The presence of openings in composite beams reduces the load capacity of these. The influence of the openings is related to the failure mode of the beams, i.e if the beam has a long span this will have a greater reduce in the load capacity if the opening is situated in the mid-span region, on the other hand the load capacity of short span beams is more affected if the openings are located near the support.

The concrete slab confers rigidity to the beam, locks the upper flange of the profile preventing buckling and provides greater resistance to shear force.

The beam span proved to be a very important parameter in the analysis of composite beams with web openings. It should be noted that the losses obtained in short span beams is higher compared to the longer spans, due to the fact that the smaller the beam span greater the influence of the Vierendeel moments.

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