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Nonlinear analysis and parametric study on steel beams with circular web openings

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Abstract. Steel beam with circular web opening have been gaining more space in the Brazilian industry. They bring countless benefits to the construction, in addition to reducing the cost, there is also a reduction in weight, allowing the passage of service ducts, which integrate the installations with the floor system. The variability of this system can make it difficult to carry out experimental tests that evaluate all possibilities, as they demand more financial, human, and time resources. Thus, numerical analysis presents as an alternative for this evaluation, seeking the best option for applying this system. Therefore, this paper aims to simulate numerically steel beams with circular web opening, using the finite element method. The analysis includes material and geometric nonlinearities, as well as the study of instability. Through experimental results performed by Morkhade and Gupta (2015), the numerical model was calibrated to carry out a parametric study that evaluates the spacing of openings (s), diameter of openings (d), height of beam web (h) and beam thickness (t). Calibration was performed by comparing the load x mid-span deflection experimental curve with the numerical one, obtaining satisfactory results. The parametric study concluded that, in general, the parameters significantly influenced in the structural behavior of the beam, except the spacing of openings.

Keywords: Steel beam with circular web openings; nonlinear analysis; parametric study; finite element method.

1 Introduction

Since 1940 engineers have been making efforts to reduce the weight of the structures and the costs of steel constructions, maintaining resistance to the forces required. From these needs, the beams with web openings emerged, and it have been gaining more space in the Brazilian industry with the automation of the manufacturing process of the profiles and the technological advance of the industries.

Steel beams with web openings bring numerous benefits to the construction process. It offer advantages both in terms of aesthetics and the functionality of the buildings, as it allow the passage of service ducts, integrating the installations with the floor system. Due to the agility in construction, ability to overcome large spans and optimization of spaces in large buildings, this structural system is widely used in industrial sheds, roofs and multi-floors buildings [1].

However, under certain boundary and loading conditions, the web openings of the beams can reduce their resistant capacity, generating stress concentration and localized instability around the web openings. Therefore, many authors propose methods to increase the stiffness of steel beams with web opening, obtaining satisfactory results regarding the resistance capacity of this structural system. Thus, the present work consists of numerically simulating steel beams with circular web openings, through the finite element method, in order to carry out a parametric study that evaluates spacing of openings (s), diameter of openings (d), height of beam web (h) and beam thickness (t).

2 Steel beam with circular web openings

Some shapes of openings are best known and used in the steel beam industry, including rectangular, hexagonal and circular. In the present work, the analyzed openings are circular, following the paper presented by Morkhade and Gupta [2].

Due to the lack of information from the national standard regarding beams with web openings and the unfamiliarity of the possibilities of this structural system, it is not used to the fullest extent of their potential. This also occurs due to the greater complexity of the design process of these beams, being the most used method the one suggested by Redwood [4], who proposes to use an equivalent rectangular opening, greatly underestimating the load capacities of the cellular steel beams.

There are more recent efforts to improve this method, such as Chung, Liu and Ko [5], who suggested an empirical model using the generalized bending-shear curve. Lawson and Hicks [6] indicate that the design of beams with web openings must conform the Ultimate Limit State (ULS), checking the bending moment, shear, Vierendeel mechanism, local and global buckling, and the Serviceability Limit State (SLS), checking the deformation, the cracking of the concrete and the vibration.

Ribeiro et al. [7] proposed a model to estimate the deflection of a simply supported beam with one or several openings in the web, fitting a semi-empirical model from numerical and experimental results. Some variables that influence the behavior of a beam with an opening were defined, among them are the ratio between the beam span and the height of the steel profile; the ratio between the diameter of the opening and the height of the steel profile; the number of openings along the beam; a form factor that relates to the geometry of the opening; and a factor that relates the inertia of the opening with the inertia of the profile.

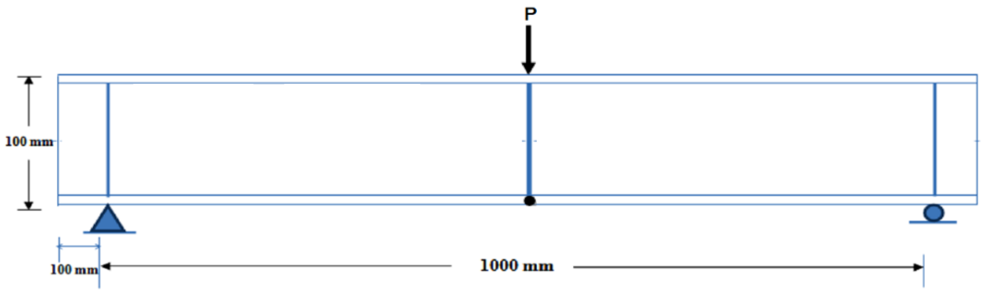
3 Numerical Analysis

Numerical simulation starts with defining a problem and creating a base model. The physical model is represented by a system of equations, simplified and approximated by methods such as the finite element method. In the present work, the numerical simulation was performed using the ABAQUS [8] and was developed in accordance with the experimental study of Morkhade and Gupta [2]. In the numerical analysis process, physical and geometric nonlinearities were considered, in addition to an instability analysis, to find the maximum load of the profiles. The material properties of the beam were obtained from the study by Morkhade and Gupta [2], being the 346,75 MPa, 465,5 MPa, 201500 MPa. Boundary and loading conditions are also based on the work of Morkhade and Gupta [2], who performed a 3-point bending test.

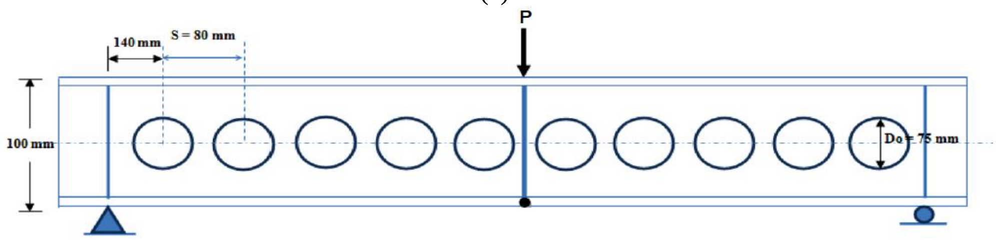
The simulation started with the analysis of the steel beam without openings, moving on to the analysis of three other beams with web opening, which present different spacing/diameter ratios (relation between the center-center distance of the openings and the diameter of the openings, s/d), as shown in Figure 1. This relationship varies only as a function of spacing, as the diameter of the openings is constant and is 75 mm. The section has an upper and lower flange width of 55 mm, the flange thickness of 5 mm and the web thickness of 4.7 mm.

Calibration is the starting point for running any numerical simulation. It consists of adjusting numerical parameters based on previously performed experimental results. In the present work, the calibration was performed by comparing experimental results performed by Morkhade and Gupta [2] with the numerical one. The hardening elasto-plastic model with a bilinear stress-strain diagram was used for the non-linear analysis. The shell element S4 was used (S = Shell; 4 = number of nodes), with a square mesh of 10 mm.

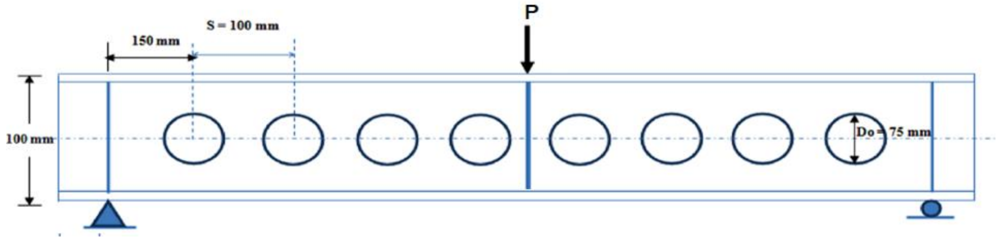
Due to the slenderness and the presence of web openings, an instability analysis is necessary for the beams studied. Initially, the dominant buckling mode is determined, and global, lateral torsional buckling is found for all beams. To proceed with the calibration of the models, the analysis of non-linear buckling was performed, finding the maximum resistant load of the beam. The simulation results, considering physical and geometric nonlinearities and instability, showed good results. The Figure 2 shows comparatively the load x mid-span deflection curves of the numerical study for each beam.



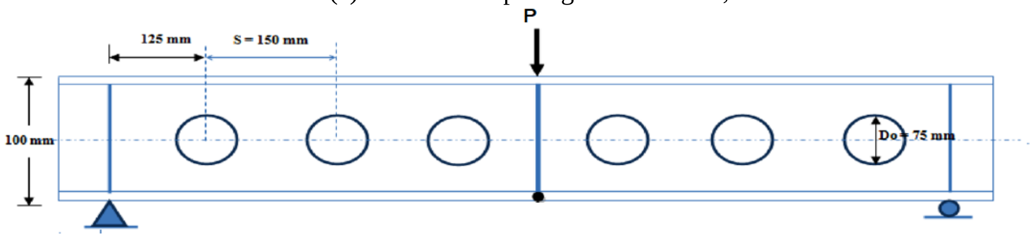
(a) SB



(b) SBWO 1: Spacing/Diameter = 1,07



(c) SBWO 2: Spacing/Diameter = 1,33



(d) SBWO 4: Spacing/Diameter = 2,00

Figure 1. (a) Steel beam, (b), (c) e (d) Steel beam with web openings tested by Morkhade e Gupta [2].

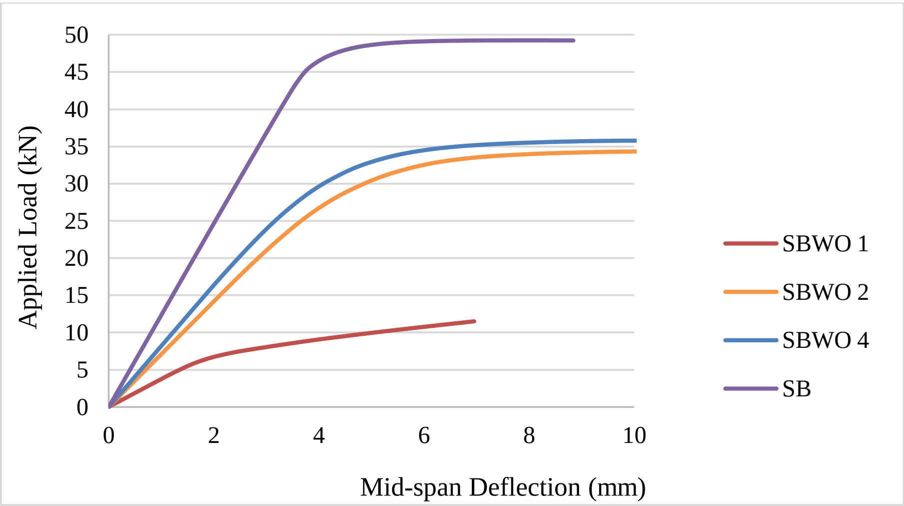


Figure 2. Applied Load (kN) x Mid-span deflection (mm) curve: Spacing of openings

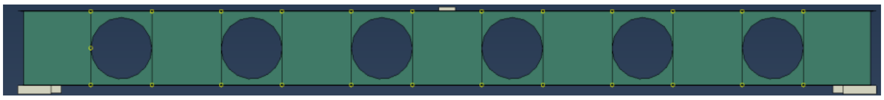
Up to this point, the variation in the number of openings in a 1 m beam has been analyzed, reaching the conclusion that the more openings there are in the beam, the lower its maximum load will be. Thus, after performing the calibration of the numerical model, the parametric study was performed, varying geometric parameters to estimate their influence on the behavior of the structure.

4 Parametric Analysis

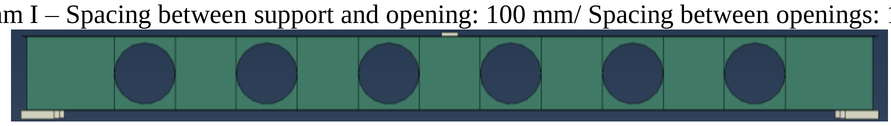
Numerical modeling aims to expand the database referring to a given structural behavior. This study substantially reduces the time and cost of solution when compared to experimental studies. Thus, parameters that would be difficult and costly to evaluate in an experimental test were chosen, namely: spacing of openings (s), diameter of openings (d), height of beam web (h) and beam thickness (t). The characteristics of each parameter, their respective results and the conclusions drawn from each evaluation are presented below.

4.1 Spacing of openings (s)

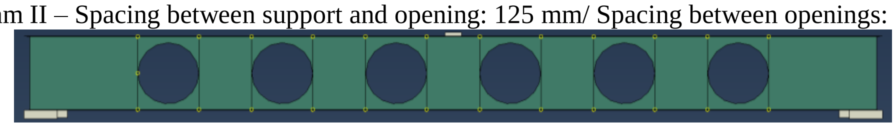
In the analysis of the spacing of openings, the number of openings was fixed at 6 and the spacing between the support and opening and between the openings were varied. The choice of this parameter is justified because it is considered in the design process and that is highlighted by Morkhade and Gupta [2]. Figure 3 shows the four modeled beams and describes the values of spacing used, while Figure 4 presents the results obtained.



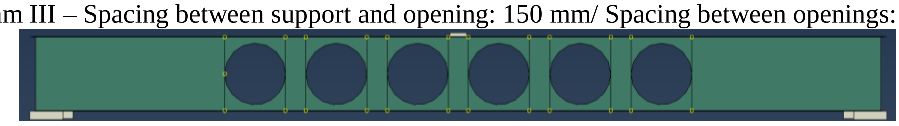
(a) Beam I – Spacing between support and opening: 100 mm/ Spacing between openings: 160 mm



(b) Beam II – Spacing between support and opening: 125 mm/ Spacing between openings: 150 mm



(c) Beam III – Spacing between support and opening: 150 mm/ Spacing between openings: 140 mm



(d) Beam IV – Spacing between support and opening: 250 mm/ Spacing between openings: 100 mm

Figure 3. Spacing of openings

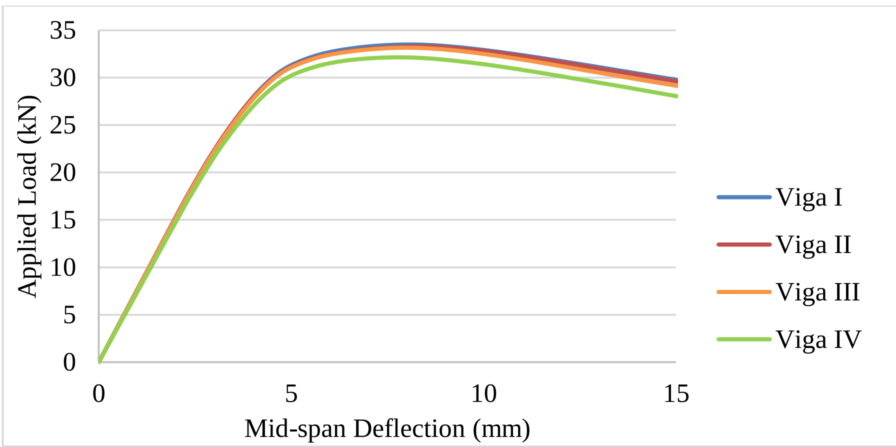


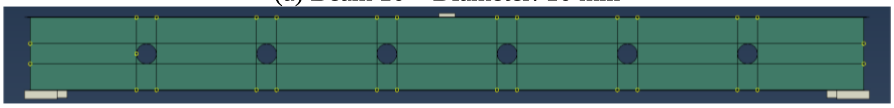
Figure 4. Applied Load (kN) x Mid-span deflection (mm) curve: Spacing of openings

Considering that all the analyzed beams had 6 openings and comparing them, it is possible to notice that in the elastic state the behavior is not influenced by the spacing between openings. In addition, the difference in maximum load between the beams in the plastic phase was very small. Thus, it can be concluded that the spacing between openings in beams with small spans does not significantly influence the maximum load.

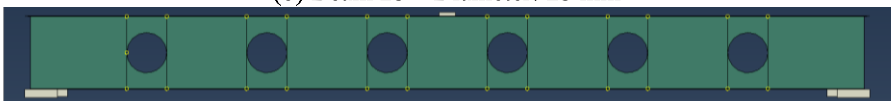
4.2 Diameter of openings (d)

The diameter of openings is a determining factor in the analysis of the maximum load of the beams, since the larger this diameter, the lower the beam stiffness and more susceptible to instabilities. In the experimental study by Morkhade and Gupta [2] it is shown that openings greater than 75% of the height of the beam are not recommended for use, thus the parametric study did not exceed the diameter of 75 mm for beams of 100 mm height, investigating smaller diameters, as shown in Figure 5. Figure 6 shows the result of the analysis.

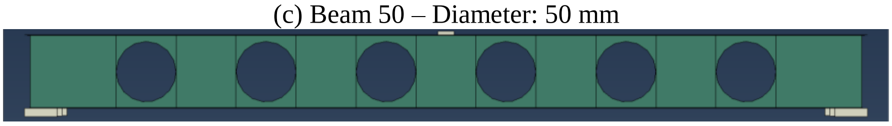
(a) Beam 10 – Diameter: 10 mm



(b) Beam 25 – Diameter: 25 mm



(c) Beam 50 – Diameter: 50 mm



(d) Beam 75 – Diameter: 75 mm

Figure 5. Diameter of openings

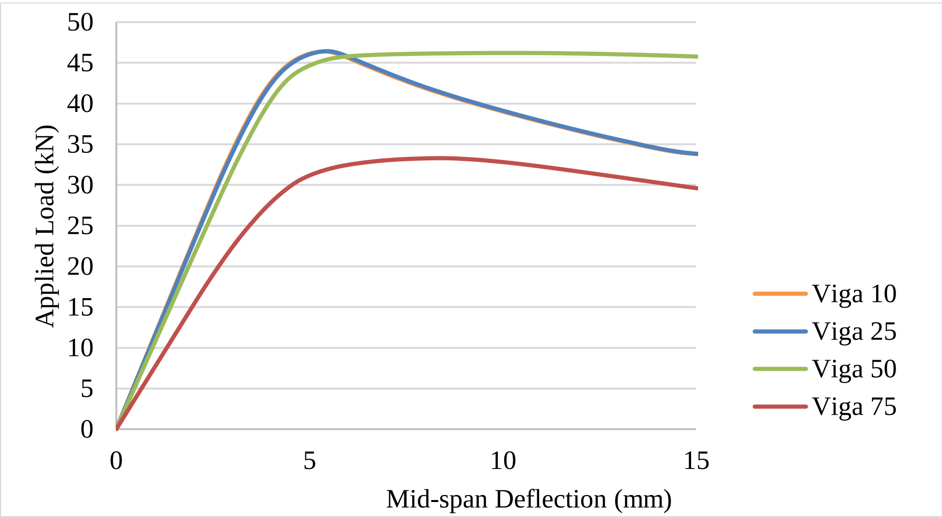


Figure 6. Applied Load (kN) x Mid-span deflection (mm) curve: Diameter of openings

From Figure 6, it is possible to see that the smaller the diameter of the openings, the greater the maximum load and the stiffer the beam. However, for diameters below 50 mm (50% of the web height), it is observed that the maximum load value does not decrease and the load x deflection curve remains the same.

4.3 Height of beam web (h)

Although the increase in height decreases the ratio between the height of the openings and the beam, this implies an increase in slenderness, so the analysis of this parameter is essential. The heights of the web beam and the results are shown in Figure 7.

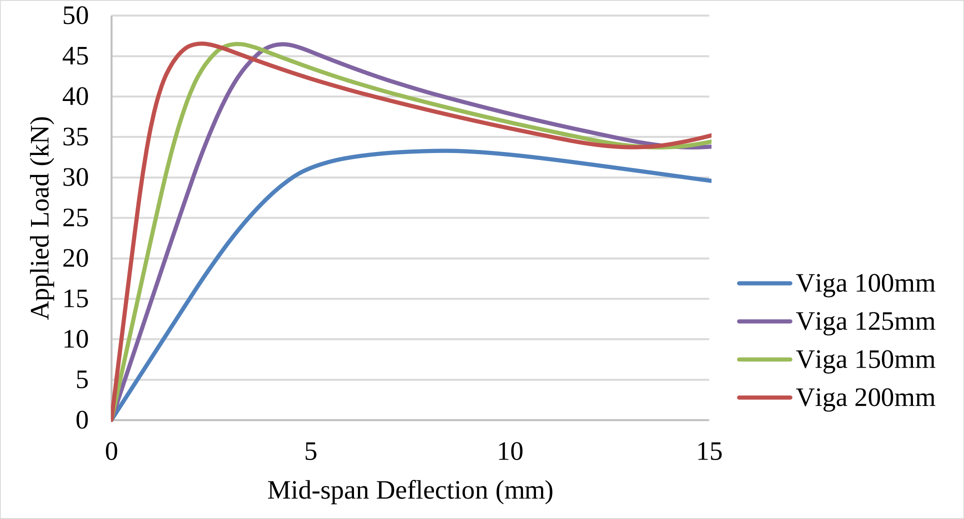


Figure 7. Applied Load (kN) x Mid-span deflection (mm) curve: Beam thickness

It was observed that the 100 mm high beam has a lower stiffness and lower maximum load than the other beams. However, from a height of 125 mm, the stiffness of the beam continues to increase, but the maximum load does not increase, due to the rise in slenderness, that make buckling predominant.

4.4 Beam thickness (t)

Increasing the thickness of the beam decreases its slenderness, meaning that instability should be less influential. Table 03 shows the different thicknesses used in the analysis, for the flange and the web, and Figure 09 presents the result of this analysis.

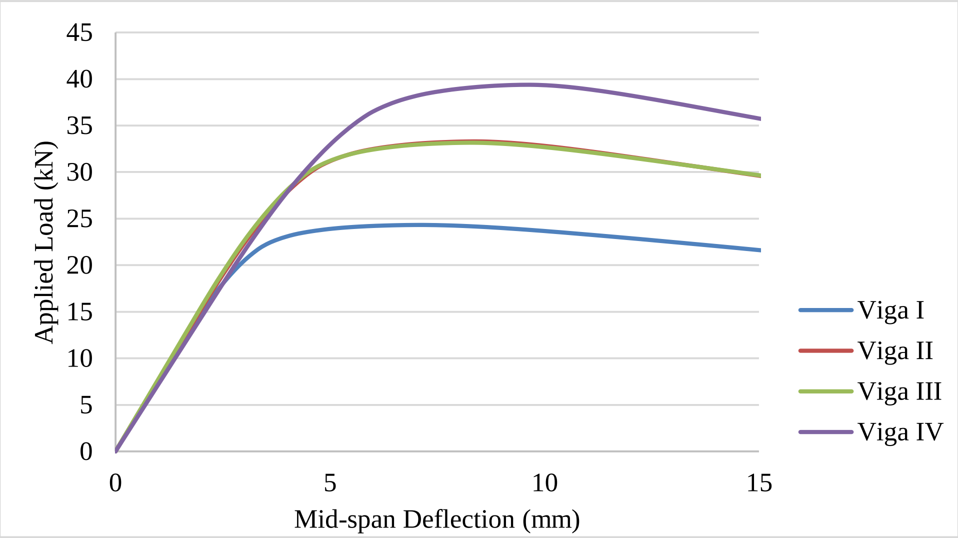


Figure 9. Applied Load (kN) x Mid-span deflection (mm) curve: Beam thickness

Table 03. Beam thickness [2]

Beams	Web thickness (mm)	Flange thickness (mm)
Beam I	4.7	5
Beam II	9.4	10
Beam III	14.1	15
Beam IV	18.8	20

As expected for this analysis, as the thickness of the web and flange increases, the maximum load also significantly increases, even with the presence of openings. It can be seen that this is a parameter that greatly influences the strength of steel beams, because with each increases in thickness (from 4.7 to 4.7 mm for the web and 5 to 5 mm for the flange), there is already a large increase in the maximum load.

5 Conclusions

Steel beams with web openings are presented as an alternative to conventional steel beams, providing weight and cost reduction and aesthetic advantages. Thus, a numerical analysis of the bending capacity of these beams was performed in a three points bending test, evaluating the spacing/diameter ratio of the openings and geometric parameters of the beam, in order to deepen the knowledge of this structural system.

Initially, the calibration was performed based on the study by Morkhade and Gupta [2], considering physical and geometric nonlinearities and instability. The results found were satisfactory and showed that the dominant buckling mode was global lateral torsional. In addition, checked that the more openings there are in the beam, the lower its maximum load will be. From the parametric study it was possible to understand the influence of each parameter and its magnitudes in obtaining the maximum load. In general, the geometric parameters analyzed significantly interfered in the structural behavior of the beam, with the exception of the spacing between openings, showing that what really interferes is the presence or absence of openings and their number along the length.

Through this work, it was possible to make a comparison with the experimental values found by Morkhade and Gupta [2] and extrapolate the results obtained by them, with analyzes that are very close to the experimental reality, confirming that numerical analysis is a great tool for predict results.

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