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NUMERICAL ANALYSIS OF THE STRESSES AND BEHAVIOR OF COMPOSITE CASTELLATED BEAMS WITH CIRCULAR HOLES

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Abstract: The primary goal of this work is to analyze, using numerical modeling, the structural behavior of Composite Castellated Beams (CCBs) made of I-steel profiles and reinforced concrete slabs. This work examines the performance of CCBs and the stress distribution around circular castellated holes. For this, a detailed numerical modeling through the Finite Element Method (FEM) using the ABAQUS/CAE software was elaborated. The results were analyzed, showing the behavior of the stresses in different circular holes of beams modeled. CCBs are important structural elements with high strengths. These strengths come from using innovative building techniques. CCBs with castellated steel profiles and reinforced concrete slabs have their height increased after construction. Castellated beams present higher stiffness without increasing the ratio of weight to length of the beams. However, the presence of holes generates complex stress states on the castellated steel beams used, and such states need to be studied for a better understanding of the behavior of CCBs.
Keywords: Composite Structures, Castellated, Finite Element Method, Steel Beams, ABAQUS.

INTRODUCTION

The technique of cutting a steel profile in the form of a pattern and then welding it again, forming a castellated profile, provides several constructive advantages, including increasing the beam's height and keeping the structure's weight. Castellating the beam provides a significant increase in load capacity and reduction of mid-span deflection under service load. This is particularly evident when contrasting castellated beams with solid steel beams (Hadeed & Hussain Alshimmeri, 2019) the castellated steel beams are used widely because of their useful structural applications and serviceable performance due to their good significant properties such as light weight, facility in construction, materials economize and strength. The castellated steel beam fabricated from its origin solid beam (I-beam.

Composite beams are the result of associating an I-shaped steel beam with a concrete slab using shear connectors, which are typically welded to the top flange of the steel I-section. The behavior of the composite beam usually presents superior resistance to the simple I steel beams with little additional cost.

The CCBs in this research result from the association of a steel profile with a sequence of regular openings in the web to a concrete slab. To keep steel I-beam connected to the concrete slab shear connectors must be utilized. The resulting beam will overcome even longer spans than the conventional composite beam. Also, there is a considerable increase in rigidity provided by the increase in the steel profile height with the openings and, consequently, the height of the entire slab-beam system is raised.

Hollow beams have zero bending stress at the centroid where the weld line is located; however, this situation is not verified when such a beam is used together with the concrete slab, as it occurs in composite beams (Cavalcante, 2005).

The complex behavior of these beams is associated with different instability effects that the castellated composite beam may be subject to in regions of negative moment where the lower compression flange of the beam is unconstrained (Gizejowski & Salah, 2011).

Therefore, the present work's main objective is the development of a non-linear three-dimensional numerical model of a composite steel and concrete beam with stud bolt shear connector and circular holes and subsequent analysis of the stress distribution on the beam.

To ensure that the model used provided reliable results, the methodology was first applied in the construction of a non-linear numerical standard model, experimentally developed by Saadatmanesh, Albrecht and Ayyub (1990) and the numerical model by Silva (2018).

BIBLIOGRAPHIC REVIEW

There are several sorts of cells that are used to create castellated steel beams: hexagonal, circular, diamond, octagonal, and with expansion plates. In this work, the focus is on castellated beams with circular cells. The manufacturing process for castellated beams is similar, no matter the type of hole, but there are different specifications for the dimensions of the hole, as shown in Figure 1.

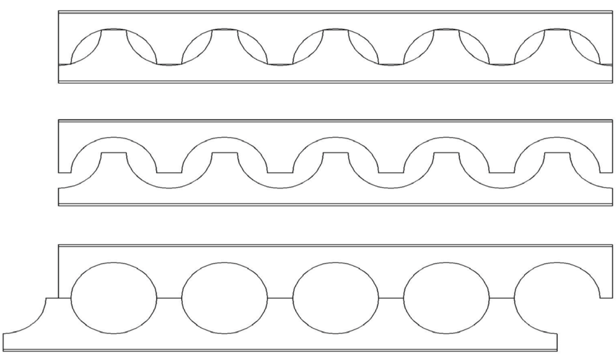

Figure 1. Manufacturing of castellated beams.

Cellular beams, with circular openings, can present different changes in opening diameters and distances between opening centers (Figure 2). According to the recommendations of the patent document (Walker, 1990), the cell pattern may be defined by the following proportions:

- The ratio between the opening diameter and the expanded beam height is equal to 0.67 ($e_1 = D_0/d_g = 0.67$).
- The ratio between the pitch and the opening diameter is equal to 1.25 ($e_2 = p/D_0 = 1.25$).

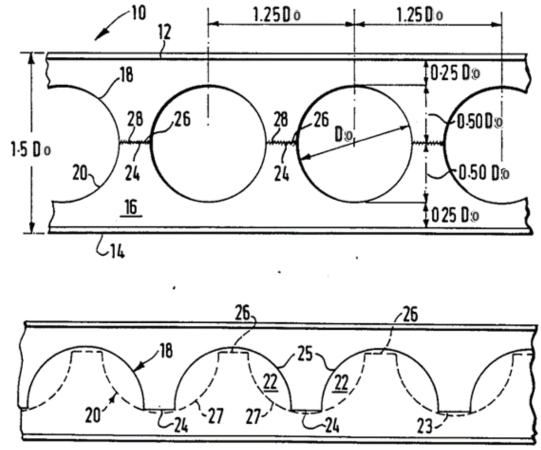

Figure 2. Circular cellular beam featured in British patent nº 4894898 (Walker, 1990).

Harper (1994) simplified the patent dimensions using ranges of values that generate satisfactory behavior in cellular beams, as shown in Figure 3.

Where:

d is the height of the full web profile.

d_g is the height of the cellular beam.

D_0 is the diameter of the opening.

and S is the C/C spacing between the two holes.

Pachpor et al. (2011) carried out a numerical and comparative analysis on hollow-core beams with circular and hexagonal holes. They concluded that the deflection in a circular opening is greater compared to hexagonal openings of the same area, as the number of openings increases.

They also calculated that the maximum Von Mises stress is also lower in the circular opening compared to the hexagonal opening of the same area, and the deflections and maximum Von Mises stresses increase as the number of openings increases.

The difference between the displacement vs. load curves on the numerical model and experimental study may be due to the assumption of perfect adhesion between concrete slab and steel beam in numerical modeling (1996).

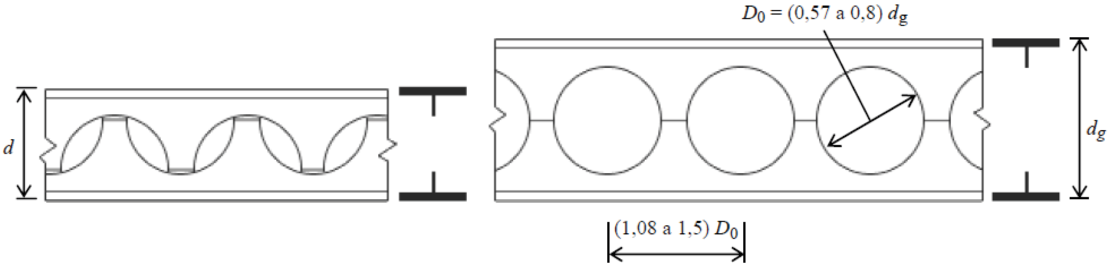

Figure 3. Geometric properties of cellular beans (Harper, 1994).

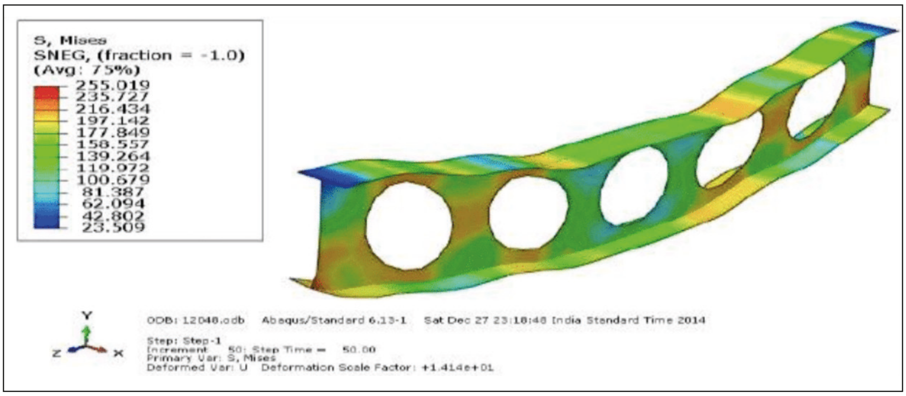

Figure 4. Variation in stresses of the optimized cellular beam (Jamadar & Kumbhar, 2015).

Jamadar and Kumbhar (2015) made a parametric study of castellated beams with hexagonal, circular, and diamond-shaped openings to optimize their size. They considered the overall depth ratio of the castellated beam to the depth of opening provided (*D/Do*) and the ratio of opening spacing to the depth of opening (*S/Do*) using the ABAQUS software (Figure 4).

They concluded that castellated beam with circular shaped openings (Cellular beam) with opening size of 0.73 times its overall depth with S/Do ratio of 1.4 and D/Do ratio of 1.41 of takes 32.5 kN load. And, in the case of the diamond-shaped opening, more shear transfer area is available, so there are minimum effects of local failure.

Figure 5 shows a graphical representation of the variation in failure load against the diameter of the circular opening hole (diameter = *Do*) in cellular beams. It is evident that load at yielding rises for diameters between 80 and 110 mm before falling after that.

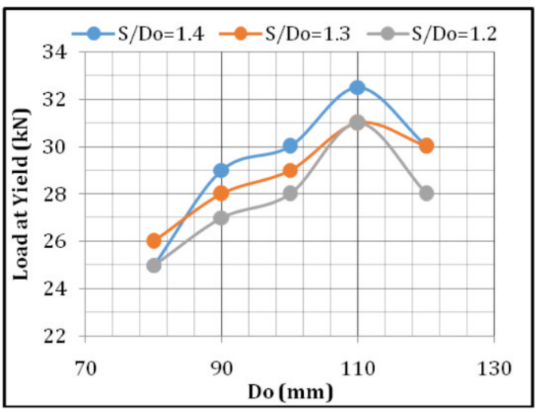

Figure 5. Variation in yield load for different S/Do and D/Do ratios for cellular beam (Jamadar & Kumbhar, 2015).

METHOD AND MATERIALS

To achieve the objectives of this research, a detailed study was carried out on the behavior of the Composite Castellated Beams (CCBs) then, based on the data obtained, numerical modeling was elaborated through the Finite Element Method (FEM) using the software ABAQUS/CAE for non-linear numerical simulations.

Since the CCB is the result of applying different construction techniques, concrete and castellated steel beam; this research will analyze the different factors that influence the behavior of this structure that can present great resistance and potential for practical applications.

For composite beams, the ABNT NBR 8800 standard (2008) states that the concrete properties must comply with ABNT NBR 6118 (2014). In this work, concrete with f_{ck} of 35 MPa will be used.

Structural I-steel profiles are commonly used because they have good ductility, homogeneity, and weldability, as well as a high ratio between ultimate resistance stress and yield stress. The steel profiles used in this study are welded profiles, which allow the formation of different web and flange geometries, beyond the options provided by the manufacturers of laminated profiles. The steel used in this research was the ASTM A-36.

Shear connectors are mechanical devices intended to ensure the joint work of the I-steel section with the concrete slab in CCBs, configuring the behavior of a composite beam. The stud bolt is one of the most used types of connectors. NBR 8800 (Brazilian Association of Technical Standards, 2008) specifies that the structural steel used in these connectors with a diameter of up to 22.2 mm must be ASTM A108-Grade 1020, and must be specified with yield strength (f_{ycs}) of at least 345 MPa, rupture strength (f_{ucs}) greater than 415 MPa, minimum elongation in 50 mm of 20% and minimum area reduction of 50%. The materials have their engineering properties listed in Table 1.

NUMERICAL MODEL

Four CCBs were modeled. One CCB is with an I-beam section profile as the standard (not castellated beam) model and the other three being castellated beams.

The shapes of the castellated beams were as follows: in type 1, the original size of the standard steel I profile is maintained, adding the holes insertion process, thus increasing its final size; in type 2, it uses a smaller steel I-profile so that when making the holes, the final size of the piece will be the same as the size of the standard beam.

In type 3, a commercial steel profile I is chosen with dimensions close to type 2 and maintaining the size of the hole. The W 200x31.3 profile was used for type 3.

All the beams have the same length of 4727 mm, the same concrete slab and the same connectors distribution.

The length of all the beams is 4727 mm, and the dimensions of the profiles are specified in Figure 6 and Table 2.

Beam	Height (mm)	Hole *Do* (mm)	Thickness of web (mm)	Weight (kg)
Silva (2018)	332.70	-	6.8	207.13
Standard	332.70	-	6.8	207.13
Type 1	500.41	350	6.8	198.09
Type 2	332,70	220	6.8	176.69
Type 3	314.28	220	6.4	117.82

Table 2. Important beam dimensions for the numerical analyses.

MODELED PARTS AND ANALYSIS METHOD

The parts are represented based on predefined finite elements available in the ABAQUS library (2014) and were chosen in this research based on the global behavior of the element, the computational effort needed, the number of degrees of freedom, and the literature review mentioned above. The reinforced concrete slab was modeled using the finite

Engineering property	Concrete	Profile (Steel A-36)	Reinforcement Steel	Connector (Steel A108)
Poisson's Ratio (v)	0.20	0.30	0.30	0.30
Density (p) [kg/m³]	2500	7850	7850	7850
Young's Modulus (E_c) [MPa]	32000	215000	200000	206000
Yield Stress (f_{ct} / f_y) [MPa]	4	411.6	500	345
Plastic Strain (f_m / f_u) [MPa]	40	565.4	-	415

Table 1. Engineering properties of materials.

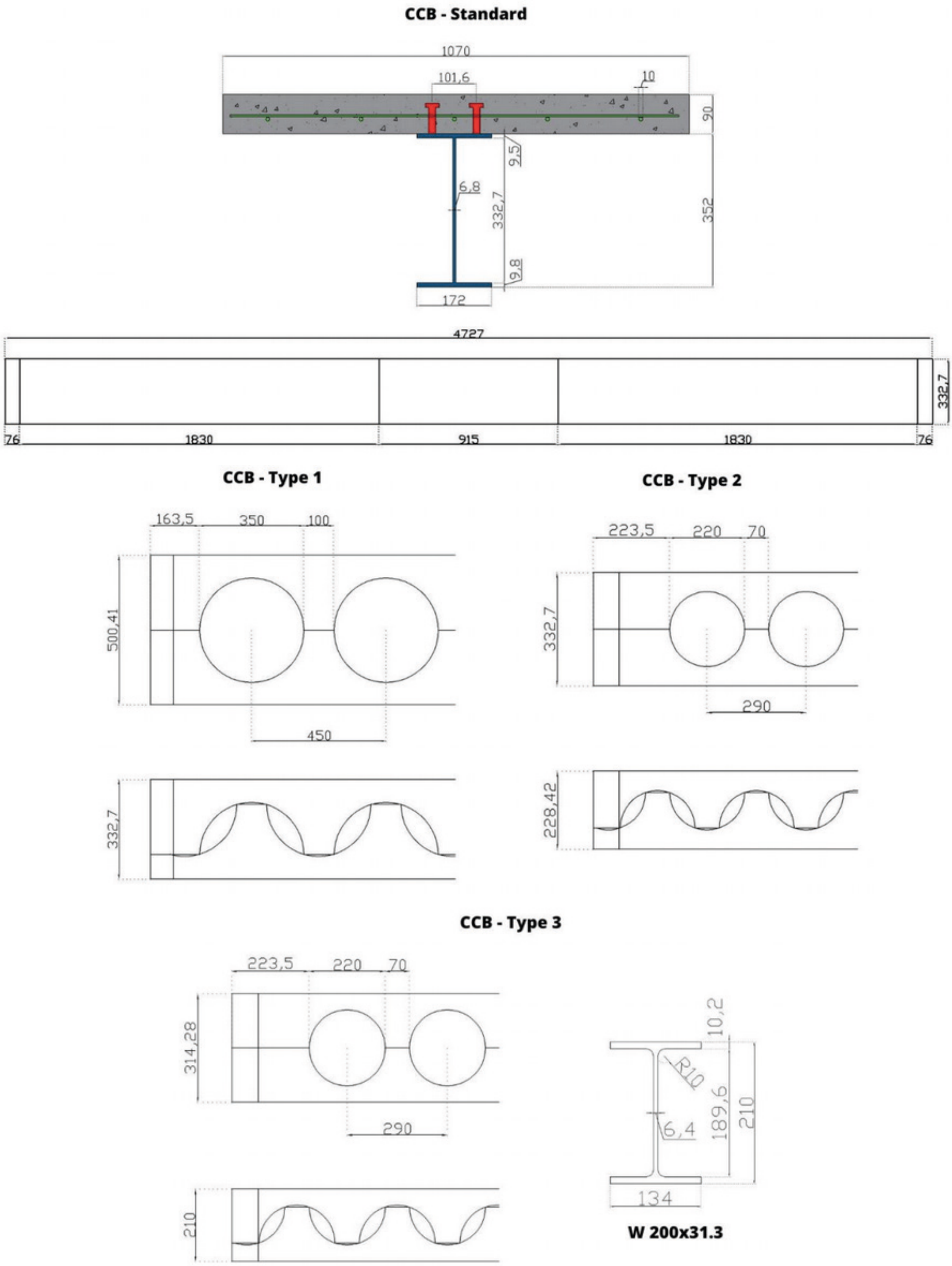

Figure 6. Profile dimensions.

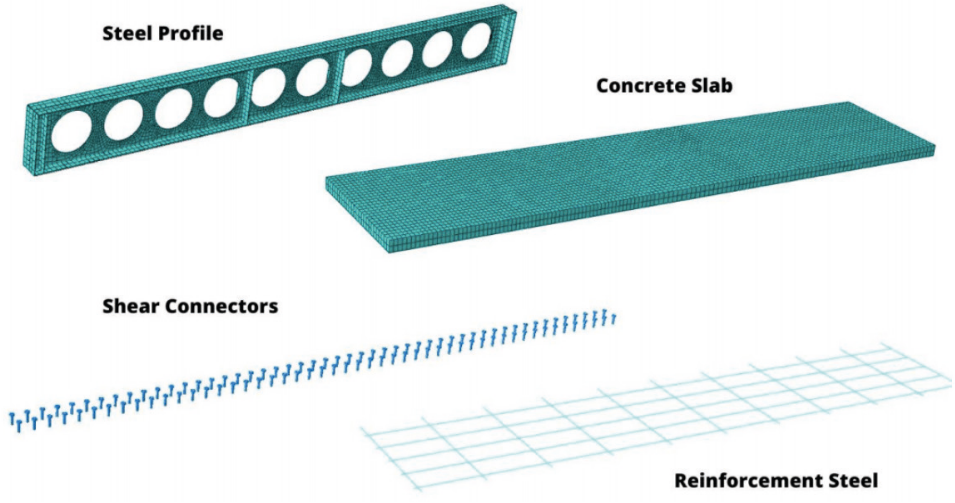

Figure 7. Modeled parts.

element SOLID C3D8R, the steel profile with the element SHELL S4R, the steel bars (passive reinforcement) with the element TRUSS T3D2, and the shear connectors with the element BEAM B31. Figure 7 shows some details.

The concrete slab has a height of 90 mm and is reinforced transversely with 11 bars and longitudinally with 5 steel bars with a diameter of 10 mm. The joint work between the steel profile and the concrete is guaranteed by shear connectors with a diameter equal to 16 mm, spaced every 93 mm in the longitudinal direction and 101.6 mm in the transverse direction.

ABAQUS/Standard is a generic analysis product capable of solving a wide range of linear and non-linear problems. In this work, a non-linear model was made (materially and geometrically), using a static response and Newton's method as a numerical technique to solve the non-linear equilibrium equations.

DEFINITION OF THE CONSTITUTIVE MODEL OF MATERIALS

To better represent the behavior of reinforced concrete, the Concrete Damaged Plasticity (CDP) model was used. The plastic damage model in ABAQUS uses the flow function proposed by Lee and Fenves (1998), which is a modification of the plastic damage model by Lubliner et al. (1989) considering the different evolutions of the tensile and compressive strengths of concrete. According to Silva (2018), this constitutive model allows the characterization, in a realistic way, of the stress vs. strain ratio of concrete, especially the loss of stiffness from the point of its maximum resistance.

For the definition of this model, five constitutive plastic parameters are needed: Dilation angle, ψ=36° eccentricity of the plastic potential surface, $\in$=0.1; ratio between the nonlinearity start stress in biaxial and axial compression $\sigma_{b0}/\sigma_{c0}=1.12$; parameter $K_c=0.6668$; and viscosity $\mu=0$.

For the plastic regime of profile steel, the constitutive model of Von Misses was adopted, and Han, Zhao, and Tao (2001) adopted the uniaxial multi-linear behavior of steel. Thus, five points of the type (tension, deformation) were inserted. The first marks the end of the elastic phase, and the last marks the beginning of perfectly plastic flow.

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For the passive reinforcement steel, the stress vs. strain diagram was adopted based on the perfect elastic-plastic model, indicated by ABNT NBR 6118 (2014). For the steel of the connectors, a bilinear diagram with isotropic work hardening was used.

DEFINITION OF INTERACTIONS, RESTRICTIONS, AND BOUNDARY CONDITIONS

For the interaction of the passive steel reinforcement and the concrete slab, the constraint of the “Embedded Region” type was used, with the reinforcement being the immersed region and the concrete slab the host region.

The union of the I-shaped steel profile with the concrete slab is modeling the shear connectors. In this case, it will be necessary to create a contact interaction between the top surface of the steel profile and the bottom surface of the reinforced concrete slab. A “surface-to-surface” contact interaction was created, with the surface of the steel profile as the “master” and the surface of the concrete slab as the “slave”. The contact properties were the normal behavior defined as “hard contact”, making the penetration of the slave surface into the master surface imperceptible, and the tangential behavior of the friction formulation “penalty”, with a coefficient of friction equal to 0.4 (Silva, 2018).

A “Tie Constrain” type coupling was made between the base nodes of the connectors and the upper surface of the steel profile. The interaction between the concrete slab and the shear connector is done using the “Embedded constrain” command.

A boundary condition of the “Mechanical” category of the type “Displacement” was created with movement restriction in all axes, except translation in the direction of the x axis (U1) and rotation around the z axis (UR3).

LOAD APPLICATION

Loading application was divided into three stages. Initial step: the boundary conditions are applied and propagated to the following steps: Step 1 refers to the application of the structure’s weight, based on gravitational action; Step 2 refers to external load application to the structure.

RESULTS AND DISCUSSIONS

In this study, a methodology for modeling the composite castellated beam was initially validated. The validation took place by comparing the results of the numerical simulation of the simply supported beam with two concentrated loads and the experimental results available in references (Ayyub et al., 1990; Silva, 2018). Silva (2018) used Ayyub et al. (1990) experimental results to make a numerical model and this paper used this model as base to the CCB Standard case.

Considering the curve “load vs. displacements” of the composite beam of Silva (2018) and the standard CCB studied in this research, it can be seen that a good agreement can be observed in Figure 9. In that figure, at displacements of 30 mm and 50 mm, in Silva´s beam, the applied loads are, respectively, 520 kN and 570 kN. Meanwhile, for the standard beam of this research, at those displacements, the applied loads are, respectively, 520 kN and 580 kN, approximately. Therefore, the standard CCB of this work is an average 2% stiffer than Silva´s composite beam.

Moreover, the quality of the curves obtained between Silva´s beam (2018) and the standard beam of this work, in terms of non-linear behavior, shows a good agreement too. They are very similar. Therefore, taking into account the differences between the two beams, it can be concluded that the numerical simulation using Abaqus can be applied to the other beams (CCB types 1, 2, and 3).

After validating the modeling methodology, The FEM was applied to the modeling of CCB with different types of circular holes (types 1, 2, and 3), to evaluate the influence of the holes in this kind of structural element. A comparison was made considering the maximum deflections and the steel profile weight, as seen in Table 3.

CBB	Maximum Displacement [mm]	Comparison	Maximum Load [kN]	Comparison
Silva (2018)	58.67	-3%	573.16	-4%
Standard	60.51	-	594.88	-
Type 1	59.63	-1%	275.67	-54%
Type 2	80.63	33%	514.92	-13%
Type 3	73.89	22%	406.24	-32%

Table 3. Maximum displacement (U2) [mm] and maximum load applied [kN] with comparison in CCBs.

CBB	Weight [kg]	Comparison	Height [mm]	Comparison
Silva (2018)	207.13	0%	352.00	0%
Standard	207.13	0%	352.00	0%
Type 1	198.09	-4%	519.71	48%
Type 2	176.69	-15%	352.00	0%
Type 3	117.82	-43%	314.28	-11%

Table 4. Steel profile weight [kg] and height [mm] comparison in CCBs.

In addition, we made a comparison with another type of connection between the composite beams, instead of modeling the shear connectors; the tie effect was also simulated, directly linking the reinforced concrete slab to the steel I-profile. The results were very similar (Figure 9) and there was no significant increase in computational effort for modeling the connectors, so it was decided to model all beams with shear connectors.

Figure 10, 11 e 12 shows the stress distribution, Von Mises, longitudinal and shear stress respectively, among the Table 5, Table 6 and Table 7 the shows the maximum values comparisons.

When comparing the CCB standard with type 1, we noticed that type 1 fails earlier than expected, however, the Von Misses stress increase by 9%, but the longitudinal and shear stresses decrease by 8% and increase by 6%, respectively, since there is an increase in the height of the profile but reduces the weight.

Comparing CCB type 2 with the CCB standard, we noticed that for the same beam height, the presence of holes provides an increase in beam strength, significantly reducing by 15% of the weight of the structure. The CCB type 2 has 472 MPa being the maximum longitudinal stress, that occurs over a hole on the right side of the bean, and 253.5 MPa the maximum shear stress that occurs between the two outermost holes.

When observing the behavior between type 2 and type 3, it is noticed how the change of the steel profile causes a significant difference in the behavior of the beam in terms of maximum stress, changing even the position of the maximum shear stress on the beam. The 70% reduction in cross-sectional area for the commercial profile, caused a reduction of 58 kg on the beam weight. However, the less cross-sectional area, also reduced the deflection in 8% and the reduction of stresses Von Mises in 1.8%, shear in 1.4% and longitudinal 0.3% on the commercial profile.

CBB	Von Misses	Comparison with standard
Standard	411.6	-
Type 1	447.9	9%
Type 2	455.9	11%
Type 3	447.6	9%

Table 5. Maximum Von Misses stress [MPa] comparison in CCBs.

CBB	Longitudinal stress (S12)	Comparison with standard
Standard	444.3	-
Type 1	454.9	92%
Type 2	472.0	99%
Type 3	470.6	98%

Table 6. Maximum longitudinal stress (S11) [MPa] comparison in CCBs.

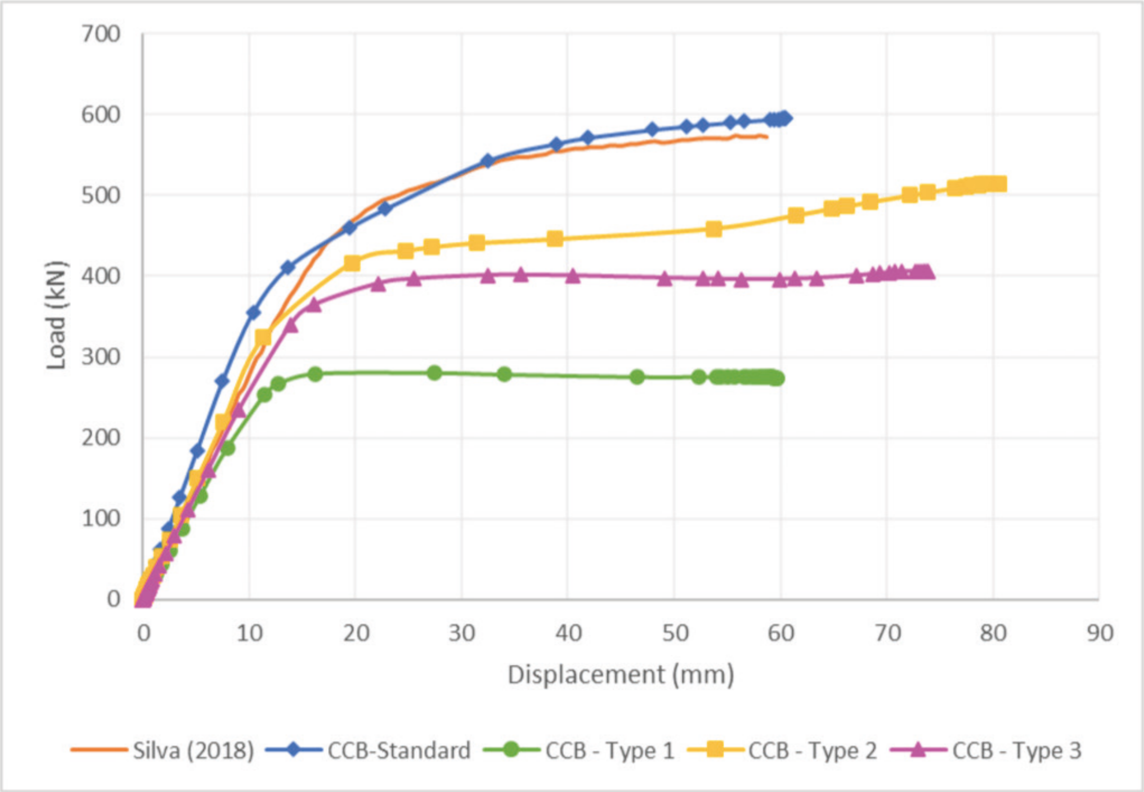

Figure 8. Load vs. Displacement curve.

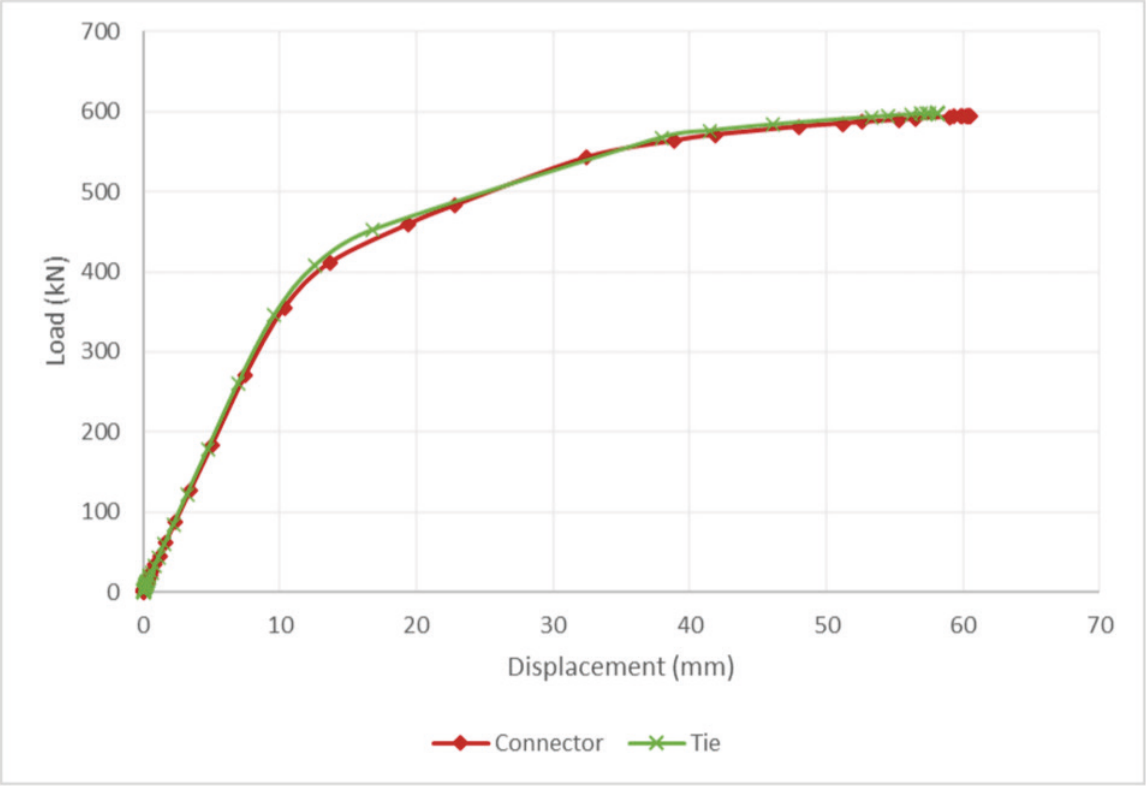

Figure 9. Load vs. Displacement curve on CCB standard.

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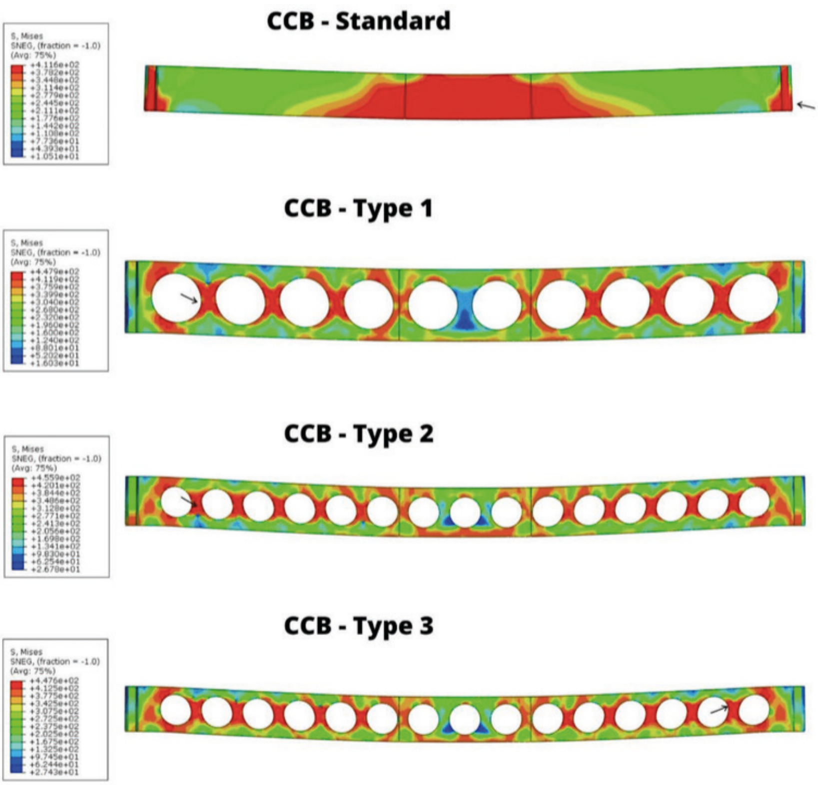

Figure 10. Von Misses stress distribution (MPa).

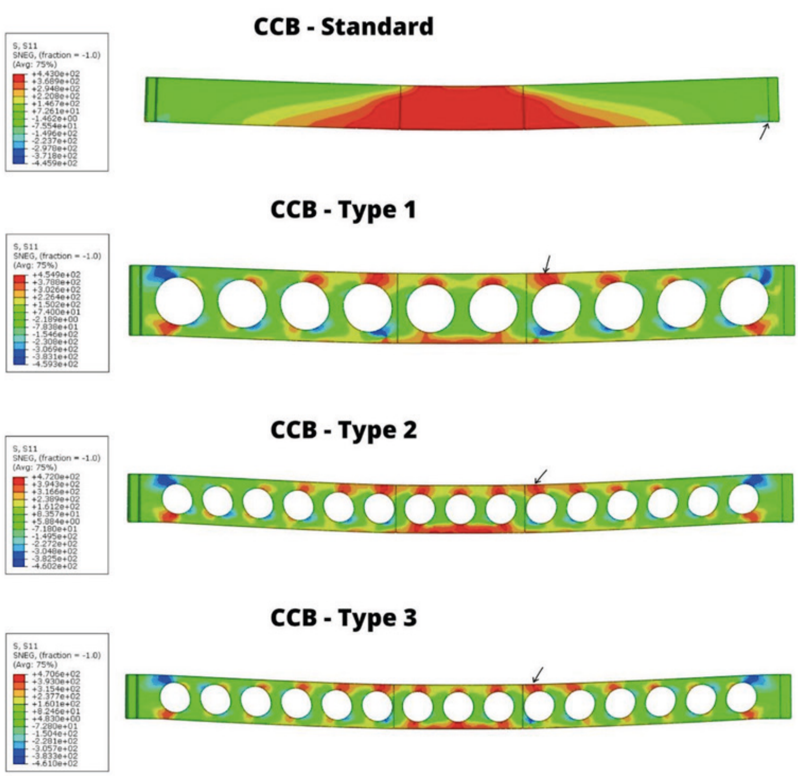

Figure 11. Longitudinal stress (S11) distribution (MPa).

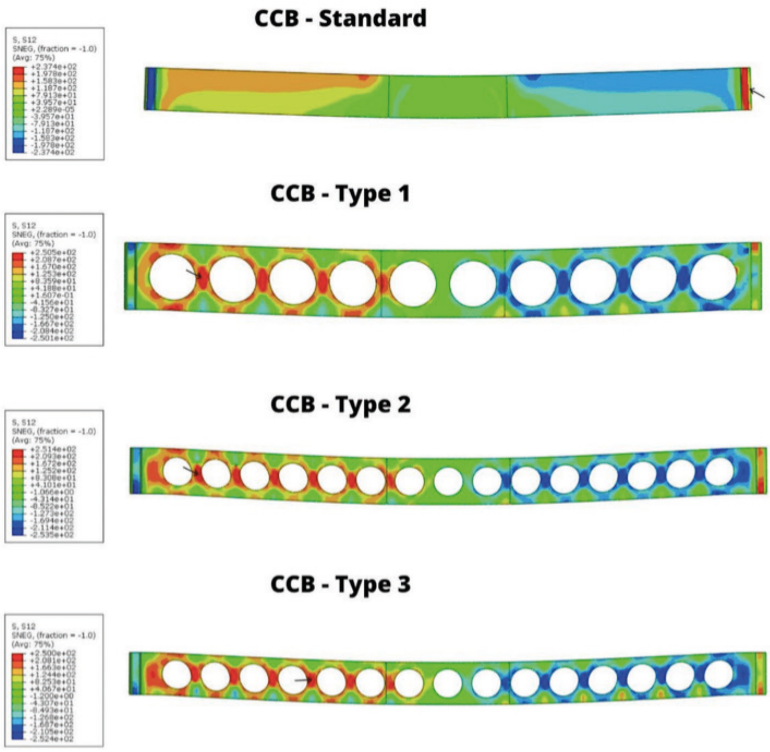

Figure 12. Shear stress (S12) distribution (MPa).

CBB	Longitudinal stress (S12)	Comparison with standard
Standard	237.4	-
Type 1	250.5	6%
Type 2	253.5	7%
Type 3	250.0	5%

Table 7. Maximum shear stress (S12) [MPa] comparison in CCBs.

Depending on the type of beam, size of the steel profile, and circular holes, the location where the maximum longitudinal stress occurs changes. On castellated beams, on the other hand, the maximum shear stress, invariably, appear in between the holes.

CONCLUSION

In this paper, a non-linear three-dimensional numerical model, using the software ABAQUS, was developed to simulate the behavior of a steel-concrete CCB with shear connectors and circular holes. The modeling methodology was validated with experimental results from the concentrated load test on a simply supported beam. The values were evaluated with the load development and the stress distribution in the profiles, proving the ability of the numerical model to simulate the behavior of the CCB.

These results corroborate works in the literature that studied composite castellated beams with shear connectors. However, it can be concluded that the reduction of the cross-sectional area for the same height and hole seizes, makes a significant difference in the behavior of the beam. It is important to highlight the need for experimental studies to better understand the behavior of steel-concrete composite castellated beams with different holes and profile types.

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