Numerical Analysis of the Stresses and Behavior of Composite Castellated Beams

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Abstract. This work has as main objective to analyze, through numerical modeling, the structural behavior of Composite Castellated Beams (CCB), with steel profile and reinforced concrete slab, in order to map the performance of the beams and the stress distribution for hexagonal castellated holes. For this, a detailed study of the CCB behavior will be done, then, based on the data obtained, a numerical modeling through the Finite Element Method (FEM) using the ABAQUS/CAE software was elaborated, and finalized with an extensive analysis of the behavior of the stresses in each type of beam modeled. This study is important because composite castellated beams are structural elements that have high strengths because they are the result of the application of various construction techniques. First, composite beams with steel profile and reinforced concrete slab increase the bending stiffness and resistance to stresses of the beam. Also, castellated beams have higher bending stiffness due to the height gain after their construction process. Therefore, the union of these techniques needs to be studied and analyze the stresses generated in the beam.

Keywords: Composite Structures, Castellated, Finite Element Method, Steel Beams.

1 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, increasing the height of the beam and maintaining the weight of the structure. Providing a significant increase in load capacity and reduction of mid-span deflection under service load when comparing castellated beam with solid steel beam [1].

Composite beams are the result of associating a steel beam with a concrete or composite slab by means of shear connectors, usually welded to the upper flange of the metallic profile. The behavior of the composite beam usually presents superior resistance to the simple steel beams with little additional costs.

However, composite steel and concrete castellated beams are the result of associating a profile with sequential openings in the web to a concrete or composite slab by means of shear connectors. The resulting beam will be able to overcame even longer gaps than the conventional composite beam, as there is a considerable increase in rigidity provided by the increase in the total height of the profile with openings and, consequently, of the slab-beam system.

Hollow beams have null normal stress bending 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 [2].

The difference between the displacement x load curves may be due to the assumption of perfect adhesion between concrete and steel in numerical modeling [3]. The hexagon that presents the best results is the one suggested by Cimadevila, Gutiérrez and Rodriguez [4] where its measures meet the following recommendations of eq. (1) and Figure 1.

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 table of the beam is unrestricted. [5].

Therefore, the present work has as main objective the development of a non-linear three-dimensional numerical model of a composite steel and concrete beam with stud bolt shear connector and hexagonal holes and subsequent analysis of the stress distribution on the beam. In order 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 e Ayyub [6] and the numerical model by Silva [7].

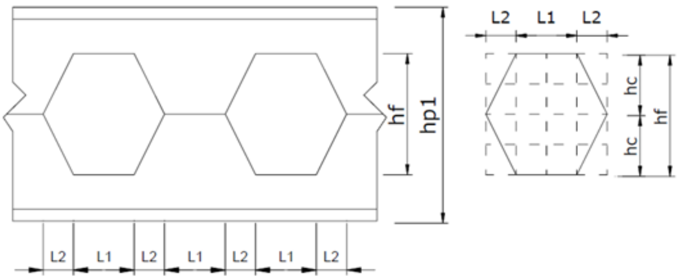

Figure 1. Hexagon details [2].

$$L_1 = 2 \cdot L_2 = \frac{h_f}{2} \tag{1}$$

2 Method and materials

In order to achieve the objectives of this project, a detailed study was carried out on the behavior of the Composite Castellated Beams (CCB) then, based on the data obtained, a 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; 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 NBR 8800 [8] standard states that the concrete properties must comply with NBR 6118 [9]. In this work, concrete with f_{ck} de 35 MPa will be used.

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

Shear connectors are mechanical devices intended to ensure the joint work of the steel section with the concrete slab, configuring the behavior of a composite beam. The stud-bolt is one of the most used types of connectors. NBR 8800 [8] 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 physical properties listed in the Table 1.

Table 1. Physical and mechanical properties of materials.

Property	Concrete	Profile (Steel A-36)	Reinforcement Steel	Connector (Steel A108)
Poisson's Ratio (ν)	0.20	0.30	0.30	0.30
Density (ρ) [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_{cm}/f_u) [MPa]	40	565.4	-	415

3 Numerical model

Four CCB were modeled, one being the standard model and three being castellated beams. Type 1 uses the same metallic profile as the standard model, but inserting the holes (Figure 2). Type 2 uses a smaller beam than when inserting the holes, the height of the beam is the size of the standard beam. Type 3 adapts type 2 using a commercial profile, in this case the W 200x19.3 profile is used, as shown in the Figure 3.

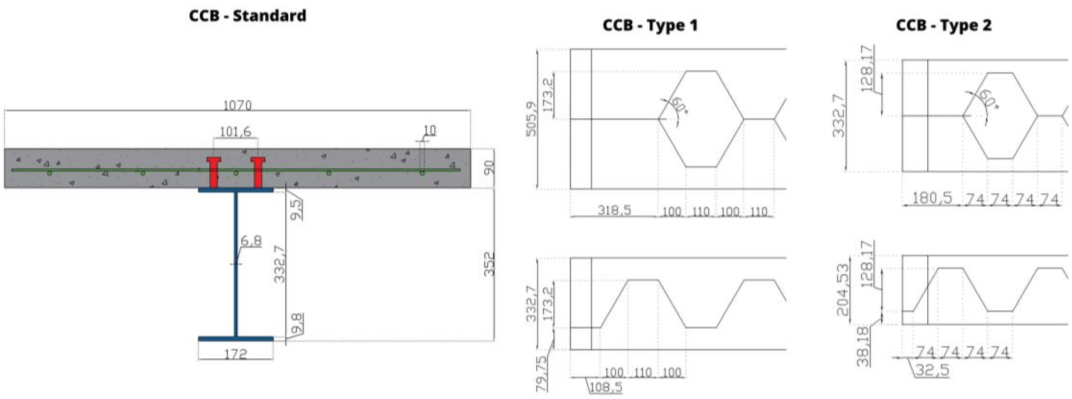

Figure 2. Profile dimensions.

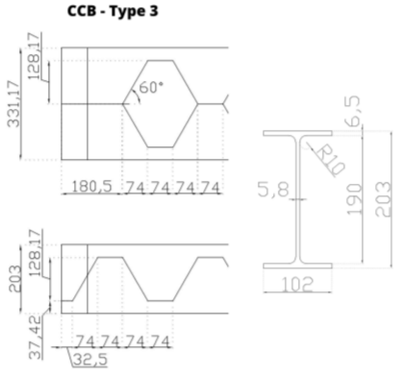

Figure 3. Commercial profile dimensions.

3.1 Modeled parts and analysis method

The parts are represented based on predefined finite elements included in the ABAQUS library [10], and were chosen in this research based on the global behavior of the element, the computational effort generated, the number of degrees of freedom and the studies that make up the literary Review. The reinforced concrete slab was modeled using the 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 4 shows the parts.

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.

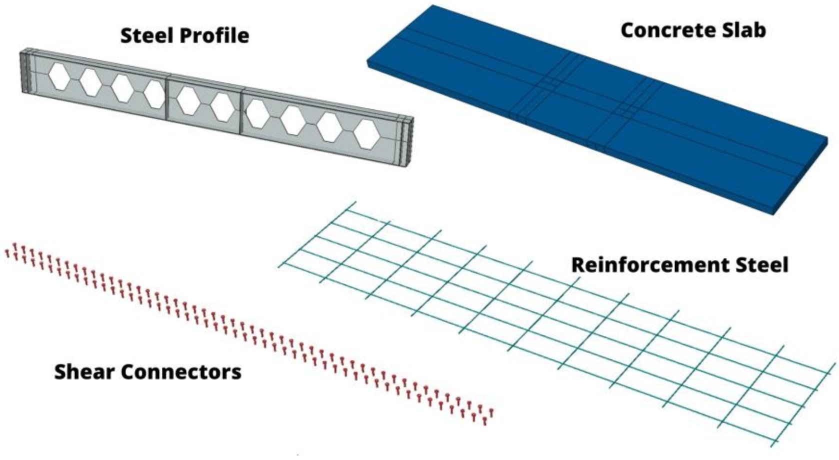

Figure 4. Modeled parts.

3.2 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 [11], which is a modification of the plastic damage model by Lubliner et al. [12] considering the different evolution of tensile and compressive strength of concrete. According to Silva [13], this constitutive model allows the characterization, in a realistic way, of the stress x strain ratio of concrete, especially the loss of stiffness from the point of its maximum resistance.

For the definition of this model, 5 constitutive plastic parameters are needed: Dilation angle, $\psi = 36°$; Eccentricity of the plastic potential surface, $\epsilon = 0.1$; Ratio between the nonlinearity start stress in biaxial and axial compression $\sigma_{b0}/\sigma_{c0} = 1.12$; Parameter $K_c = 0.6667$; and Viscosity $\mu = 0$.

For the plastic regime of profile steel, the constitutive model of Von Misses was adopted and the uniaxial multi-linear behavior of steel, also adopted by Han, Zhao e Tao [14]. Thus, 5 points of the type (tension, deformation) were inserted. The first marking the end of the elastic phase and the last marking the beginning of perfectly plastic flow.

For the passive reinforcement steel, the stress x strain diagram was adopted based on the perfect elastic-plastic model, indicated by NBR 6118 [9]. For the steel of the connectors, a bilinear diagram with isotropic work hardening was used.

3.3 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 slab the host region.

The union of the 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" and with a coefficient of friction equal to 0.4 [7].

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, with the exception of translation in the direction of the x axis (U1) and rotation around the z axis (UR3).

3.4 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 own weight, based on gravitational action; Step 2: external loads were applied to the structure.

4 Results and discussion

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 double supported beam with two concentrated loads and the experimental results [6], [7]. A good agreement was observed between the numerical and experimental results, as shown in the Figure 5. After validating the modeling methodology, it was applied to the modeling of CCB with different types of hexagonal holes, in order to evaluate the application of the holes in this type of structural element.

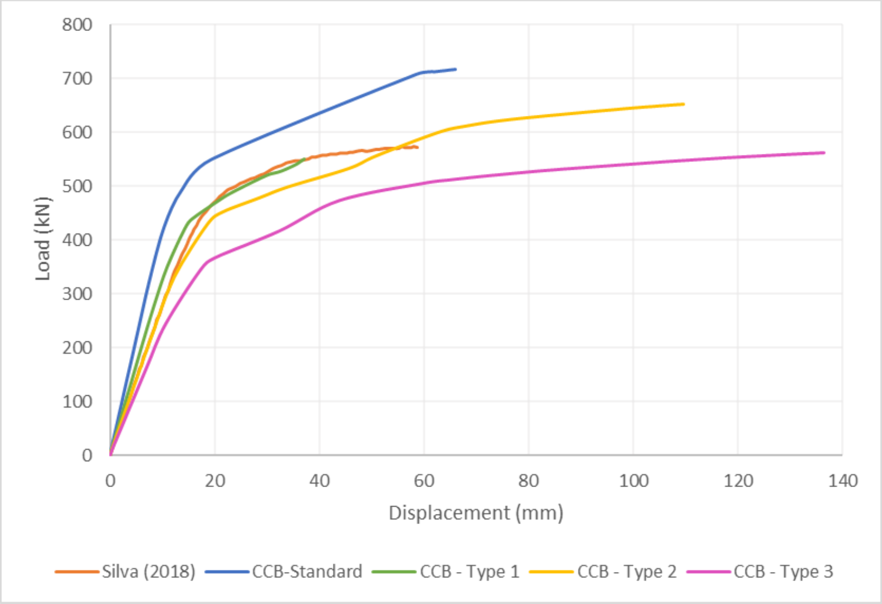

Figure 5. Load x Displacement curve.

When comparing the CCB standard with the type 1, we noticed that the type 1 fails earlier than expected, however, the stress, both Von Misses and longitudinal, increase by 5%, since there is an increase in the height of the profile, but keep the same weight. Figure 6 and Table 2 shows the Von Misses stress on the CCB beams.

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 the weight of the structure, with 262.8 MPa being the maximum longitudinal stress in CCB type 2, that occurs between the two outermost holes, and 237.4 MPa that occurs at the ends between the stiffeners (Table 3).

When observing the behavior between the type 2 and the type 3, it is noticed how the alteration of the steel profile causes a great difference in the behavior of the beam as a whole, changing even the position of the maximum stress on the beam. The 47% reduction in cross-sectional area for the commercial profile resulted in an increase in deflection of approximately 24%, but increases the Von Misses stress in 7% and reduces the longitudinal stress in 9% on the commercial profile.

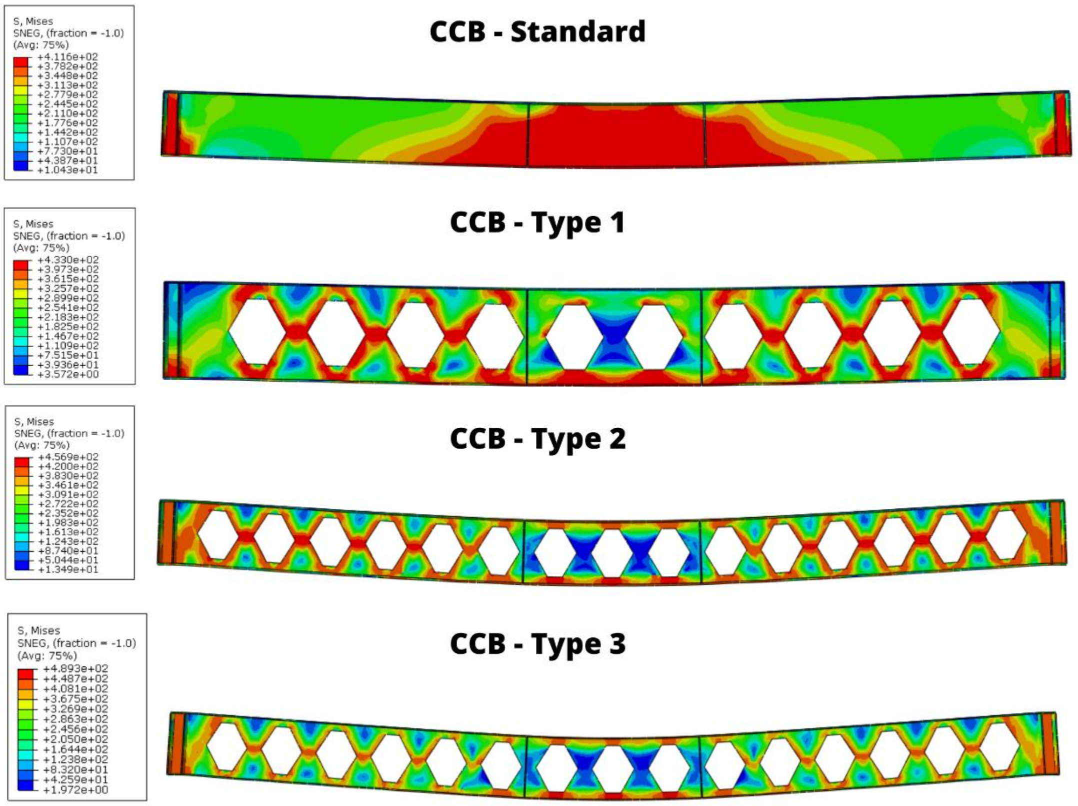

Figure 6. Von Misses stress distribution (MPa).

Table 2. Von Misses stress [MPa] comparison on CCBs.

CBB	Von Misses	Comparison with standard	Position
Standard	411.6	-	In supports
Type 1	433.0	5%	Between outer holes
Type 2	456.9	11%	Between outer holes
Type 3	489.3	19%	In the lower middle of the span

Table 3. Longitudinal stress (S12) [MPa] comparison on CCBs.

CBB	Longitudinal stress (S12)	Comparison with standard	Position
Standard	237.4	-	Between stiffeners
Type 1	249.8	5%	Between outer holes
Type 2	263.6	11%	Between outer holes
Type 3	239.2	1%	Between stiffeners

5 Conclusions

In this paper, a non-linear three-dimensional numerical model, using the software ABAQUS, was developed in order to simulate the behavior of steel-concrete Composite Castellated Beam with shear connectors and hexagonal holes. The modeling methodology was validated with experimental results from the concentrated load test on a double-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 heigh and hole seizes, makes a significant difference on 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 profiles types.

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