Numerical modeling of composite steel-concrete beams with truss type shear connector

Paulo Henrique Roberto Moura[1], Jerfson Moura Lima[1], Gustavo Henrique Silva Rodrigues[1].

[1] *Federal University of Ceará, Campus Russas*
Felipe Santiago Street - N° 411, Cidade Universitária, Russas - CE, CEP 62900-000, Brazil
paulo.henrique@ufc.br, jerfson.lima@ufc.br. gustavosilva@alu.ufc.br.

Abstract. Numerical analysis, when properly calibrated, presents itself as an important tool for the study and development of new technologies. The truss type shear connector appears as a technically and economically viable alternative, however its use in composite steel and concrete beams still needs to be studied and analyzed. For this reason, in the present work, a non-linear three-dimensional model of composite steel and concrete beams with lattice shear connector was developed, seeking to analyze the efficiency of the alternative connector. The methodology used in the modeling was validated through experimental studies in the literature.

Keywords: truss shear connector, numerical modeling, composite steel and concrete beams.

1 Introduction

The shear connectors are mechanical devices whose function is to guarantee joint work between the concrete slab and the metallic profile. Currently, only the stud bolt and laminated profile “U” connectors are standardized by the ABNT NBR 8800:2008[2] standard. However, according to Barbosa [1] and Veríssimo [3], the stud bolt connector has a series of disadvantages, among them: the low resistance capacity and the need for a 225 kV generator for its application. Cavalcante [4] points out that the main disadvantages of the “U” laminated profile shear connector are the low productivity and the incompatibility with formwork systems incorporated into the slab.

In this context, Barbosa [1] developed an alternative shear connector formed from CA-50 steel that is easy to execute, with a lower cost than the stud bolt and which has a high value of resistant capacity: the truss type shear connector Fig. 1 and Fig. 2.

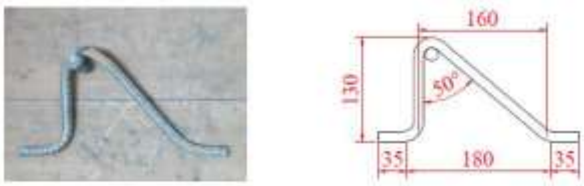


Figure 1. Straight truss type shear connector

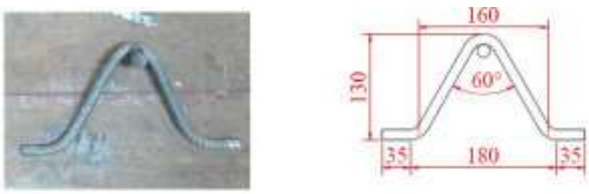


Figure 2. Isosceles truss type shear connector

Several experiments have been carried out by the University of Brasília, evaluating the behavior of the lattice connector in a push-out test. However, for it to be used in everyday composite beams, tests must be carried out with these beams. However, the high cost and time used become limiting for experimental tests in this way, according to Elloboy and Young [5], when these factors are taken into account, numerical models are presented as effective alternatives.

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 truss type shear connector and subsequent analysis of the connector efficiency. In order to ensure that the model used provided reliable results, the methodology was first applied in the construction of a non-linear numerical model of the push-out test, experimentally developed by Barbosa [1].

2 Push-out test

The methodology to be used in the study of composite steel and concrete beams with truss type shear connector was previously used for modeling a push-out test with a truss type shear connector, having its results validated with the data of Barbosa [1]. This first modeling aimed to validate the methodology created for this study. Therefore, a non-linear three-dimensional numerical model was developed using the ABAQUS 14.1 software. And, later, the results were validated by the experimental test by Barbosa [1], where 24 push-out test models were tested distributed between the isosceles and straight truss type shear connectors and stud bolt connector. The steps followed to model the test are presented below.

2.1 Definition of the parts

The software adopted, ABAQUS 1.14, does not have a system of pre-established units, being up to the user to enter coherent units, so the millimeter, mm, for the length, the Newton, N and for the tensions, the megapascal, MPa were adopted. The push-out test consists of 4 elements: profile, truss type shear connector, slab and complementary reinforcement. In the present study, the complementary reinforcement was not modeled in order to make the model simpler. Thus, 3 parts were created to constitute the push-out test. The slab and the profile were created through extrusion, while the connector was discretized as a wire element, as Sousa [6] and Carneiro [7]. The dimensions of the parts are: 750x150x100, for the slab strip; 750x14,2x100 for the metal profile, both in coordinates (x,y,z) and in mm. In the case of the lattice connector, the points that define its geometry (0,0) were inserted; (33.21,57.01); (66.43,115.06); (75,120); (83.57,115.06); (83.57,115.06); (116.7868, 57.0150); (150,0) and later connected forming the connector.

2.2 Definition of materials

Three materials were defined: CA-5O Steel for the shear connector, MR250 Steel for the profile and concrete for the slab. The properties and constitutive models of each of them are presented below.

2.3 Steels CA-50 and MR250

For the MR250 steel of the profile that was tested by Barbosa [1], due to the low stress levels developed in the steel profile, it was modeled considering only its elastic properties, as also adopted by Lima [8]. This consideration reduces the computational cost of the simulation and provides satisfactory results. Thus, the following were entered: The modulus of elasticity E = 210000 MPa, the Poisson's ratio, $\nu = 0.3$ and the density of the material, 7.85 x 10-6 kg/mm³.

For the connector steel, CA-50 steel, elastic and plastic properties were inserted in order to make the constitutive model more complex and to be able to analyze the non-linear behavior. The values for the elastic properties were taken from the results obtained by Barbosa [1]. For the elastic properties, the modulus of elasticity E = 195300 MPa and Poisson's ratio, $\nu = 0.3$, were adopted. For the plastic regime of steel, the constitutive model of Von Misses was adopted and the uniaxial tri-linear behavior of steel, also adopted by Lima [8]. Thus, 2 points of the type (tension, deformation) were inserted. The first marking the end of the elastic phase (fy = 595.3MPa,0) and the second marking the beginning of perfectly plastic flow (fu = 716.6 MPa, εu = 60‰) and the material density, 7.85 x 10-6 kg/mm³.

2.4 Concrete

As a constitutive model of concrete, the Concrete Plastic Damage Model (CPDM) (Alfarah, López-Almansa and Oller [9] and Lopez-Almansa, Alfarah and Oller [10] and Lima [8]) was adopted, which considers the main failure mechanisms for concrete in tension and compression, respectively cracking and crushing. Alfarah, López-Almansa and Oller, [9]; Lopez-Almansa, Alfarah and Oller, [10] consider that this method is one of the best to represent the complex behavior of concrete, as it combines elastic isotropic damage with a non-associative plastic flow rule. For the definition of this model, 4 constitutive plastic parameters are needed: Parameter KC = 0.7, dilation angle, φ = 13°, Ratio between the nonlinearity start stress in biaxial and axial compression, $fb/fc0$ = 1.16 and Eccentricity of the plastic potential surface, ϵ=0.1 adopted as in the works above.

In addition to the model (CPDM) elastic and plastic properties were added. The elastics were extracted from Barbosa [1] and are: concrete secant modulus of elasticity Eo = 28420.23 MPa and Poisson's coefficient ν = 0.2. The non-linear behavior of concrete for tension and compression were added from the uniaxial behavior of concrete for tension and compression, as in the work of Alfarah, López-Almansa and Oller [9] and Lima [8]. The compressive strength was 34 MPa. The density of the material was 2.5 x 10e-6 Kg/mm³.

2.5 Definition of geometry and analysis method

The set was created from the geometry defined by EN 1994-1:2004 [11], being modeled approximately ¼ of the complete test, the profile table, 2 truss type shear connectors and a slab. The numerical model of the push-out test developed is very complex because it analyzes the non-linearity of two different materials, steel and concrete, in addition to analyzing the complex interactions between the materials. Therefore, like Lima [8], it was decided to process the model using the Dynamic Explicit method. Although it is a dynamic analysis method and the model is static, when the load is applied in a slow time, it is possible to do a quasi-static analysis. This control is done from a defined load application amplitude. In this study, the smooth step type was adopted.

2.6 Definition of interactions and restrictions

For maximum application of the connectors, the friction between the slab and the metallic profile was removed through frictionless interaction. For the interaction of the connector with the slab, the embedded region interaction was adopted, which guarantees a joint operation of the parts. The tie constraint of the numerical model, applied between the connector base and the profile table, provides the same behavior as the weld in the experimental program. Constraints were applied so that the partial model provides results compatible with the experimental model. Thus, a movement constraint in x (U1=0) was added on the face of the slab strip. On the lower face of the profile, the displacement in the y-axis direction (U2=0) was restricted. On the side faces of the table and slab, the displacement in the direction of the z axis (U3=0) was restricted, so that the deformations are concentrated in the x axis and in the y axis.

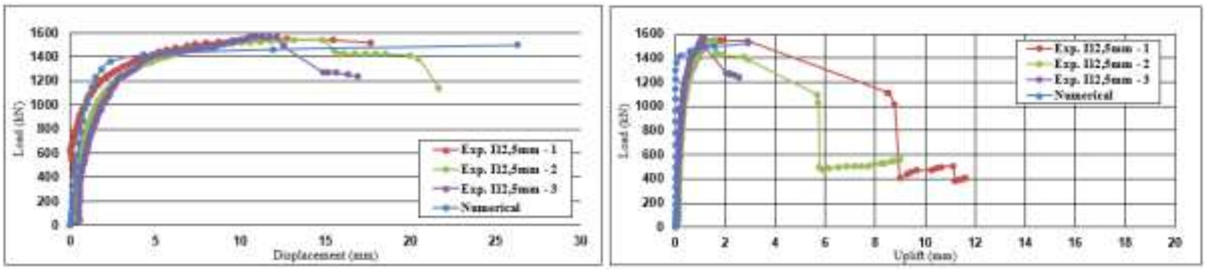
2.7 Applied Load and Finite Element Mesh

The 12.5mm isosceles truss type shear connector was simulated. To simulate the load of the experimental model, a load in the form of pressure applied to the face of the metallic profile was adopted. Element C3D8R, ABAQUS [12] was adopted for the slab strip, with 25 mm, and for the profile, with 10 mm. The connector was discretized with element B31, ABAQUS [12], with 20 mm in length.

2.8 Push-out modeling results

To validate the model, the curves were analyzed: Load x Longitudinal slip, Load x Uplift, the deformation of the connectors and the values of maximum loads. In the graphs in Fig. 3, four curves are plotted: three experimental and one numerical. In Tab. 1 are the values referring to the maximum loads of the experimental models and the numerical model. And finally, in Fig. 4, the deformed images of the experimental and numerical connector are shown.

From the qualitative analysis of the graphs, a good conformation of the numerical curve with the experimental ones can be seen. Quantitatively, from the graph of Load x Longitudinal Slip, the maximum load value of the numerical model is defined, reaching an error of 6.8% as shown in Tab. 1 with respect to experimental models.



(a) (b)

Figure 3. Curves (a) Load x Longitudinal slip. (b) Load x Uplift graph

Table 1. Maximum load reached by the numerical model in relation to the experimental.

Experimental model	Maximum load (kN)	Numerical model Maximum load (kN)	%
Exp. I12,5 - 1	1548,60		5,51
Exp. I12,5 - 2	1540,80	1463,69	5,04
Exp. I12,5 - 3	1570,00		6,80

In Fig. 4, it is possible to visualize the similar behavior between the connector tested experimentally and the modeled connector, with the stem in tension (on the right) and the stem in compression (on the left). Finally, the discretization of the connector via a linear element guaranteed a processing time of approximately 5 min, with a lower computational cost.

Figure 4. Deformed by the experimental Barbosa connector [1] and deformed by the numerical model

In view of the above, it can be concluded that the model satisfactorily simulates the push-out test with truss type shear connector and the applied methodology proves to be effective for the study of composite steel and concrete beams with truss shear connector.

3 Numerical model of composite steel and concrete beams with truss shear connector

With the validated methodology, it is possible to apply it in the study of composite steel and concrete beams with truss type connector. Initially, the design of a composite beam with a span of 9 m with a slab thickness of 15 cm and a collaborative width of 100 cm was carried out. For this situation, Profile I with parallel face W 410 x 53.0 of ASTM A572 steel was adopted. Then, with the aid of the equation developed by Lima [8], the resistant capacity of the 12.5 mm isosceles truss type shear connector was determined and later the number of connectors to obtain a beam with a total connection degree.

The creation of the numerical model followed the same parameters of the push-out test model. In order to reduce the computational cost, only ¼ of the composite beam was modeled. The slab framework consisted of transverse and longitudinal bars with a diameter of 8 mm, spaced every 200 mm. The model was subjected to a linearly distributed load along the entire beam. For the materials, the same constitutive models were adopted. For the connector steel and slab reinforcement, the characteristic values of CA-50 steel were used (fy = 500 MPa and fu = 540 MPa), and for the profile, the properties of ASTM A572 steel (fy = 345 MPa and fu = 450 MPa). In this modeling, the non-linearity of the profile steel was considered. As it is a complex model where nonlinearities of materials and interactions between components are analyzed, the model was processed by the Dynamic Explicit Method, which was able to analyze the previous model and provide satisfactory results.

For the interactions between the parts, it adopted a tie for connecting the legs of the connectors and the profile, embedded for the connector and the slab and frictionless between the slab and the profile. The embedded constraint is also adopted to consider the slab reinforcement. As for the boundary conditions, the mid-span cross section, slab and profile were restricted for displacement in the z axis (U3=0). For the face of the longitudinal axis, the x-axis displacements (U1=0) were restricted. And for the partition of the lower table, the null displacement in y (U2=0) simulating the 2nd gender support. Finally, the C3D8R element was adopted for the slab strip, with 50 mm, and for the profile, with 30 mm. The connector was discretized with beam elements with 6.7 mm in length. The slab reinforcement was modeled with truss elements with a size of 5 mm. Fig 5. presents the model.

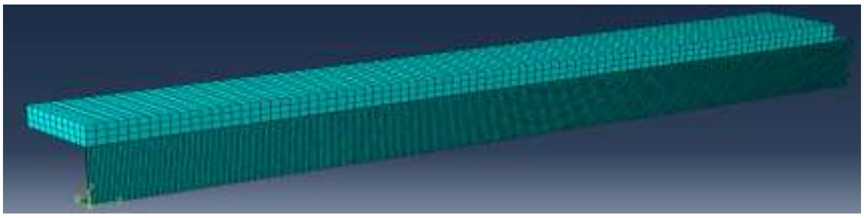


Figure 5. Numerical model of the composite steel and concrete beam

4 Results and discussion

In this study, a methodology for modeling the composite steel-concrete connection with the truss type shear connector was initially validated. The validation took place by comparing the results of the numerical simulation of the push-out test with lattice connectors and the experimental results of Barbosa [1]. A good agreement was observed between the numerical and experimental results. After validating the modeling methodology, it was applied to the modeling of a steel-concrete composite beam with truss shear connectors, in order to evaluate the application of the truss connector in this type of structural element.

Figure 6 presents the curve resistant moment x vertical displacement in the middle of the span. It can be seen that for initial load levels, up to approximately 400 kN.cm, the behavior is linear. From this load level, the behavior becomes non-linear until it reaches failure. Figure 6 also illustrates the strength of the composite beam obtained with the Plastic Rigidity Method (MRP), used by various regulations (EN 1994-1-1:2004 [11], AISC 360:2005 [13], AISC 360: 2010 [14], AS 2327.1:2003, ABNT NBR 8800:2008 [2],) for the design of steel-concrete composite beams. The resistance capacities obtained with the MRP and by the numerical model were 720.28 kN.m and 764.25 kN.m, respectively, a difference of only 5.75%. This indicates that the numerical model developed was able to adequately simulate the behavior of steel-concrete composite beams with truss connectors. Furthermore, this result indicates that the truss type connector can be applied in the steel-concrete connection of composite beams.

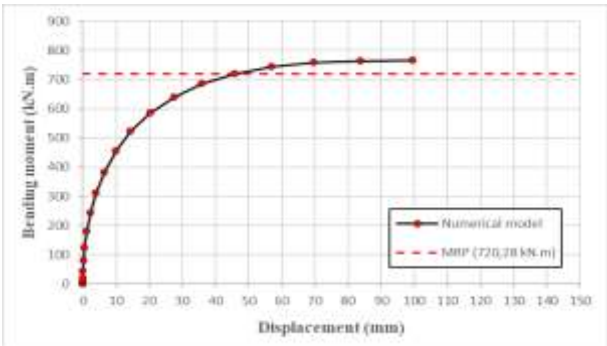


Figure 6. Resistant moment x displacement curve

Still from the numerical model, it is possible to obtain the slip along the composite beam for different levels of loads, as illustrated in Fig. 7. It is observed that up to 60% of the last moment (Mul) (458.55 kN.m) the slip values were practically null, corroborating the linear behavior of the resistant moment x displacement curve. For higher load levels, the connectors suffered deformations, allowing the development of higher slip values along the beam, thus generating the beginning of the non-linearity of the resistant moment x displacement curve. It can also be seen that the highest slip values occurred at the end of the beam, the region where the highest longitudinal shear flow occurs. These results are in agreement with studies of composite beams with conventional shear connectors, indicating once again the efficiency of the lattice connector.

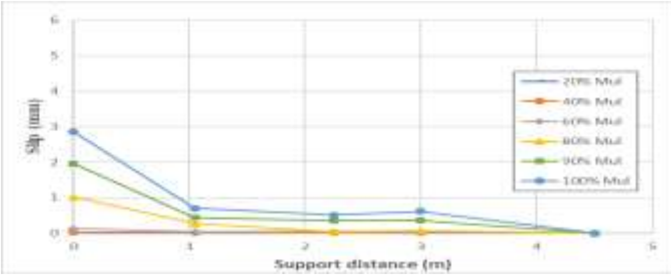
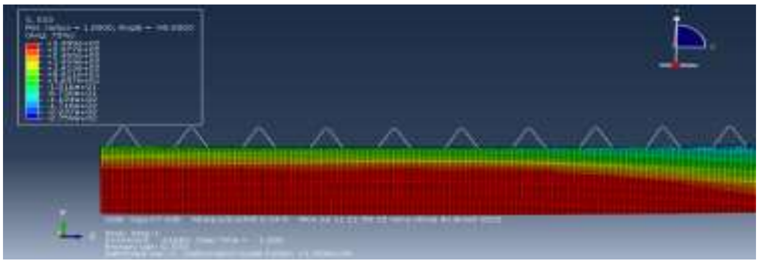
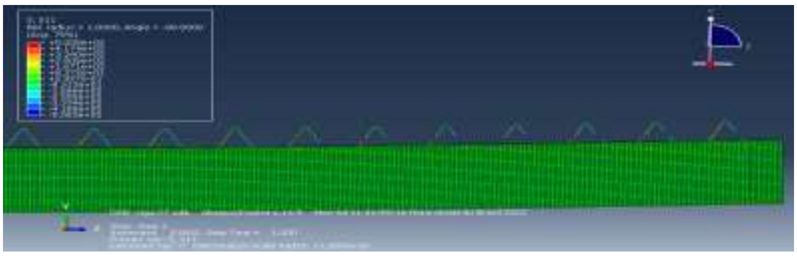


Figure 7. Slip along the composite beam

Fig 8 shows the stress distributions in the profile (mid-span) and in the connectors at the end of the model (support), at the moment of rupture of the model. In Fig 8-a, the profile stresses in the longitudinal direction (Z) are indicated. By the stress levels, the profile is in yielding, and in all its height, it is under tension, indicating that the connectors are offering a total connection and that the neutral line of the section is in the slab. In Fig 8-b, it can be seen that the connectors are more stressed at the ends, with stresses reaching the yield strength of the steel that constitutes the connectors. Note that one of the rods works under tension and the other under compression.



(a)



(b)

Figure 8. Stress distribution (MPa). (a) Longitudinal stresses in the profile at mid-span of the beam. (b) Axial stresses in beam end truss type shear connectors.

5 Conclusions

In this paper, a non-linear three-dimensional numerical model was developed in order to simulate the behavior of steel-concrete composite beams with truss shear connectors. The modeling methodology was validated with experimental results from the push-out test. The result of the resistance capacity of the composite beam with truss type connector obtained numerically was compared with that obtained analytically with the Method of Plastic Rigidity. The difference in the strength values was approximately 5%, proving the ability of the numerical model to simulate the behavior of the composite beam with truss type shear connector. In addition, the slip values were evaluated with the load development and the stress distribution in the profile and in the connectors. These results corroborate works in the literature that studied composite beams with conventional shear connectors. However, it can be concluded that the truss type shear connector has great potential to be applied in the steel-concrete connection of composite beams. It is important to highlight the need for experimental studies to better understand the behavior of steel-concrete compo]site beams with truss type shear connectors.

References

[1] BARBOSA, W. C. S. Estudo de conectores de cisalhamento em barras de aço para vigas-mistas de aço-concreto. Brasília, 2016, 511p. Tese de Doutorado em Estruturas e Construção Civil. Departamento de Engenharia Civil e Ambiental. Universidade de Brasília, Brasília, 2016.
[2] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT NBR 8800: Projeto de estruturas de aço e estruturas mistas de aço e concreto de edifícios. Rio de Janeiro, 237 p., 2008.
[3] VERÍSSIMO, G. S. Desenvolvimento de um conector de cisalhamento em chapa dentada para estruturas mistas de aço e concreto e estudo do seu comportamento. Belo Horizonte, 2007, 290p. Tese de Doutorado em Estruturas, Escola de Engenharia, Universidade de Federal de Minas Gerais, 2007.
[4] CAVALCANTE, O.R.O. Estudo de Conectores de Cisalhamento do Tipo 'V' em Vigas Mistas. Brasília, 2010, 192p.Tese de Doutorado em Estruturas e Construção Civil. Departamento de Engenharia Civil e Ambiental. Universidade de Brasília, Brasília, 2010.
[5] ELLOBODY, E.; YOUNG, B. Performance of shear connection in composite beams with profiled steel sheeting. Journal of Constructional Steel Research, v. 62, n. 7, p. 682–694, 2006.
[6] SOUSA, Joseanne Alves de. Modelagem numérica de vigas mistas aço-concreto utilizando conectores de cisalhamento treliçados. 2019. 62 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Civil) - Universidade Federal do Ceará, Campus de Russas, Russas, 2019.
[7] CARNEIRO, E. S. Estudo numérico de conectores de cisalhamento tipo isósceles para vigas mistas de aço e concreto. 2021. 74 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Civil) - Universidade Federal do Ceará, Campus de Russas, Russas, 2021.
[8] LIMA, J. M.; (2018). Estudo da capacidade resistente do conector de cisalhamento treliçado via Método dos Elementos Finitos. Dissertação de Mestrado em Estruturas e Construção Civil, Publicação E.DM-12A/18, Departamento de Engenharia de Civil e Ambiental, Universidade de Brasília, Brasília, DF, 88p.
[9] ALFARAH, B.; LÓPEZ-ALMANSA, F.; OLLER, S. New methodology for calculating damage variables evolution in Plastic Damage Model for RC structures. Engineering Structures, v. 132, n. January, p. 70–86, 2017.
[10] LOPEZ-ALMANSA, F.; ALFARAH, B.; OLLER, S. Numerical simulation of RC frame testing with damaged plasticity model comparison with simplified models. 2nd European Conference on Earthquake Engineering and Seismology, n. November 2015, p. 1–12, 2014.
[11] EUROPEAN COMMOTTEE FOR STANDARDIZATION. (2004). 1994-1-1: Eurocode 4 - Design of composite steel and concrete structures - Parte 1-1: General rules and rules for buildings.
[12] ABAQUS, User's Manual, Version 6.14-4, Dessault Systèmes Simulia Corp, Providence, RI, USA, 2014.
[13] American Institute for Steel Construction. AISC 360. Specification for Structural Steel Buildings. Chicago, 2005.
[14] American Institute for Steel Construction. AISC 360. Specification for Structural Steel Buildings. Chicago, 2010.