Comparative analysis between the shear resistance of the Truss Type shear connector and stud bolt

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Abstract. Shear connectors are extremely important in the functioning of composite steel-concrete structures, as they are responsible for carrying out the transmission of forces between the steel beam and the concrete slab. The Truss Type shear connector is an alternative connector that aligns efficient structural behavior, agility of execution and low cost of production when compared to conventional shear connectors (stud bolt, for example) applied in composite structures. However, due to the short time of existence, there is still a lack regarding the understanding of the mechanical behavior of the Truss Type connector. Thus, this study aims to perform a comparative analysis between the shear resistance of the Truss Type connector and stud bolt. This study was conducted from the development of a non-linear three-dimensional finite element numerical model for simulating push-out tests with Truss Type connector. The results showed that the Truss Type connector has a strong capacity and a higher load/cross section ratio than stud bolt, even when manufactured with materials with identical properties.

Keywords: Composite steel-concrete structures, Truss Type shear connector, Finite element analysis.

1 Introduction

In recent years, intense studies and use of composite steel-concrete systems have been taking place in the field of civil engineering, mainly in the sector of construction of bridges and buildings. The adoption of this system offers cost efficiency and structure execution (Kim et al. [1]). The composite structural elements consist of the combination of materials, so that their main characteristics are explored. Composite steel-concrete beams, for example, are designed so that steel is primarily responsible for supporting tensile stresses and concrete for compression stresses. In general, the composite steel-concrete beam is more rigid and less expensive when compared to equivalent structural steel or reinforced concrete beams, thus justifying its use.

For the operation of composite steel-concrete structures, it is essential to guarantee the transmission of efforts that occur at the interface between components. This transmission is carried out by mechanical devices, known as shear connectors. When applied to composite beams, the shear connectors resist shear forces at the steel-concrete interface and prevent uplift between the steel beam and the concrete slab.

The shear connectors are usually welded to the steel beam and immersed in the concrete slab. The choice of type and the knowledge of the mechanical behavior of the shear connector are extremely important, because as mentioned, it is through it that the transfer of efforts at the steel-concrete interface occurs (Cavalcante [2]).

Worldwide, stud bolt is the most used shear connector in composite steel-concrete structures (Kim et al. [1]; Cândido-Martins et al. [3]). However, some drawbacks, such as the relatively low shear resistance and the need for a high-power generator (about 225 kVA) for application, depreciate the adoption of stud bolt as a shear connector. This fact has encouraged new research that aims to develop alternative shear connectors (Leonhardt et al. [4]; Verissímo [5]; Cavalcante [2]).

With the intuition of offering a shear connector manufactured with low-cost material, with reduced dependence on specific equipment in its application and with geometry with potential for application in various construction processes of composite structures, Barbosa [6] developed the Truss Type (TT) shear connector. The TT connector (Fig. 1) is produced with CA-50 steel rebars folded in a triangular shape. The CA-50 steel is considered a relatively low-cost material available in the civil construction market, and moreover, it does not require specific equipment in the welding process. From a structural point of view, the TT connector has good behavior in longitudinal slips and uplift, as well as high values of shear resistance when compared to stud bolt (Barbosa [6]; Bezerra et al. [7]).

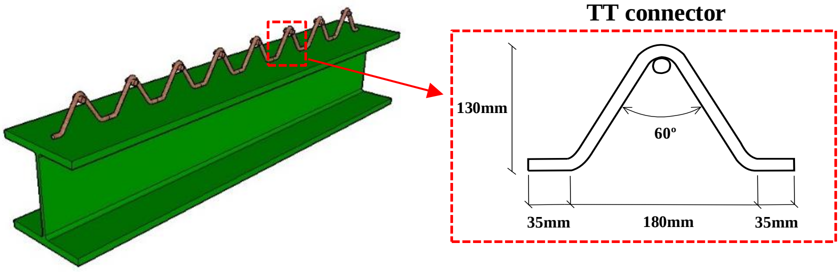

Figure 1. Truss Type shear connector

Despite the good results obtained by Barbosa [6], further studies need to be carried out to obtain a better understanding of the behavior of the TT shear connector and that its mechanical efficiency is proven for different situations. Thus, this work aims to perform a comparative analysis between the shear resistance of TT connector and stud bolt. This study was conducted from the development of a non-linear three-dimensional finite element numerical model for simulating push-out tests with TT connector. The push-out test is standardized by EN 1994-1-1 [8] and is performed to determine the mechanical behavior of shear connectors. The numerical models developed were calibrated and validated with Barbosa's [6] experimental tests.

2 Development of the numerical model

For the development of the numerical model of the push-out with TT connectors, the ABAQUS software was used. The model consists of connectors, concrete slab, steel beam and reinforcement of the slab. The interaction between these components is extremely important for the simulation of the push-out test. All sources of non-linearity (materials and contact) were taken into account in the analysis.

The experimental push-out models tested by Barbosa [6] were used in this study. These experimental models were based on the standard push-out model found in EN 1994-1-1 [8]. Only one modification was made in relation to the standard model, where 100 mm in the length of the slab was added, for better accommodation of the TT connectors, with the consequence of adding another crossbar in the reinforcement of the slab. Figure 2 illustrates the geometry of the push-out model with TT connectors. For more details on the geometry model, see Barbosa [6] or Bezerra et al. [7]. In order to reduce the computational cost during the numerical analysis, it took advantage of the symmetrical geometric of the push-out, modeling only a quarter of the experimental model.

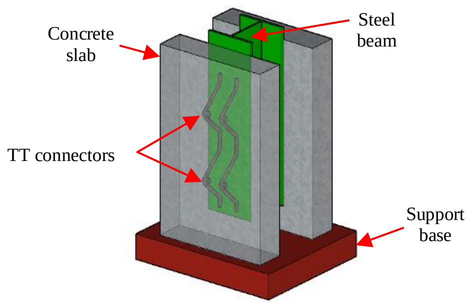

Figure 2. Geometry of the push-out model

Each component of the model was modeled separately, thus constituting independent meshes. The slab was modeled with two types of elements. In the region away from the connectors, C3D8R elements were used, while the region closes to the TT connectors, due to the geometry of the connector, C3D4 elements (three-dimensional tetrahedral element with four nodes) were applied. The TT connector was modeled with C3D8R elements in the linear regions (inclined legs, horizontal legs and pin at the top of the TT connector) and C3D4 in the curved regions, the steel beam only with C3D8R elements and the slab reinforcement bars with truss elements with two nodes and 3 degrees of freedom in each node (T3D2). The finite element mesh of the model can be seen in Fig. 3. The finite elements used in the model, present in the ABAQUS library, can be used in nonlinear analyzes, including contact, large deformations, plasticity and failure, as necessary in the numerical push-out simulation.

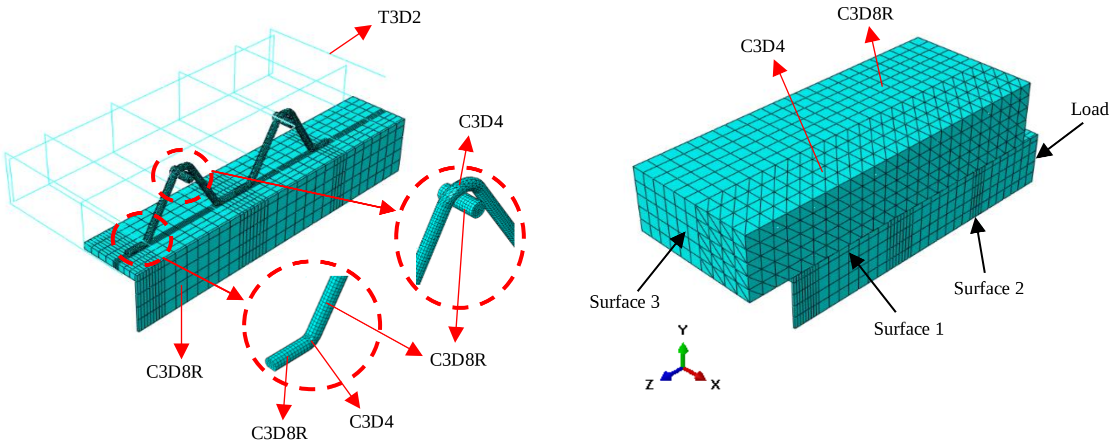

Figure 3. Mesh finite elements, load and boundary conditions of the model

Appropriate restrictions and contact interactions have been applied to simulate the interaction between model components. The connection of the horizontal legs of the TT connector with the steel beam flange was performed with a tie restriction (rigid connection). The connector-concrete interface also received the tie constraint. In the contact interaction between the steel beam flange and the slab, the following properties were considered: frictionless tangential behavior (without friction) and normal hard behavior (does not allow the penetration of one surface over the other). The slab reinforcement bars were embedded in the concrete slab.

The applied boundary conditions aimed to make the geometric simplification of the model prevail and to simulate the push-out test. On Surface 1 (Fig. 3) the displacements of all nodes in the X direction were restricted. On the surface of the web section of the steel beam (Surface 2) (Fig. 3), displacements on all nodes in the Y direction were prevented. The boundary condition related to the push-out test, consisted of restricting the displacement of the nodes of Surface 3 in the Z direction (Fig. 3). The load was applied evenly distributed in the cross section of the steel beam, as seen in Fig. 3. In this numerical model, load control was used. For the model processing, the Explicit Dynamic Method was used, widely applied in numerical simulations of push-out tests (Bezerra et al. [7]; Nguyen and Kim [9]; Qureshi and Lam [10]).

For the modeling of materials, the constitutive models Concrete Damage Plasticity were used for concrete and PLASTIC for steel, present in the libraries of the ABAQUS software. The material properties applied for each component of the model are shown in Barbosa [6]. For more information on the implementation of the constitutive models in the ABAQUS software, see Lima [11].

3 Validation of the numerical model

The numerical model developed was related to the experimental push-out model I-12.5 by Barbosa [6]. The TT connectors that make up the I-12.5 model have a diameter of 12.5 mm. The validation was performed by comparing the load-slip curves and rupture modes obtained experimentally and numerically.

The load-slip curves obtained by the experimental tests were compared with the numerical curves obtained by the developed model, as seen in Fig. 4. A good fit is observed between the experimental and numerical curves, proving the efficiency of the finite element model proposed in this study. Regarding the ultimate load of the push-out model with TT connector, the average of the experimental and numerical results was 1553.15 kN and 1492.88 kN, respectively. There is a proximity between the results, with a difference of only 3.88% between the values of ultimate load numerical and experimental. As the studied push-out model has eight connectors, the TT connector shear resistance can be determined by dividing the model's ultimate load by eight.

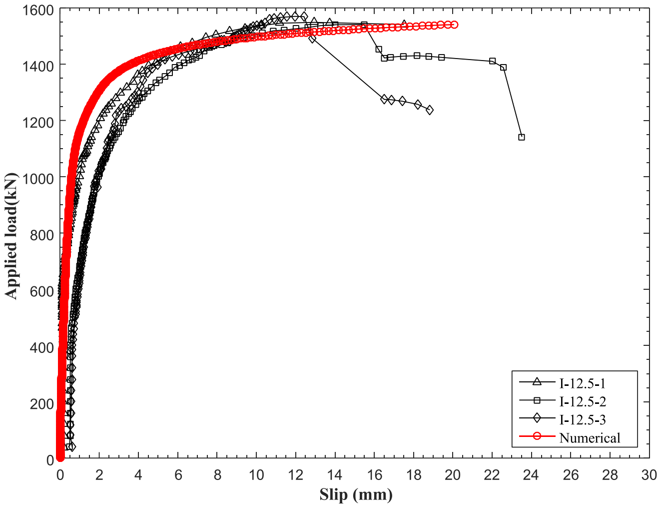

Figure 4. Load applied versus slip for push-out with TT connectors

The failure modes that occurred in the numerical simulations were also compared with the experimental models. As in the observations of Barbosa [6], it was found that the mode of rupture of push-out models with TT connectors consists of the combination of rupture by traction of one of the legs of the TT connector and the crushing of concrete in the regions near the base of the connectors. These results demonstrate the ability of the proposed finite element model to numerically simulate the behavior of the TT shear connectors.

4 Comparison between the shear resistance of the TT connector and the stud bolt

The TT connector was developed in order to offer a viable alternative to the use of stud bolt, since it is manufactured with low-cost material (CA-50 steel) and is easily available in the civil construction market, moreover, it does not require specific equipment in the connection process to the steel beam (weld). Regarding the shear resistance, Barbosa [6] and Bezerra et al. [7] from experimental push-out tests found that the TT connector has a higher ultimate load/cross section ratio than stud bolt, as seen in Tab. 1. The tested stud bolt connectors (S-19.0) had a diameter of 19 mm and a height of 130 mm, manufactured with ASTM A108 steel with yield stress 345 MPa and ultimate stress 415 MPa. The concrete properties were the same for the tests of both connectors.

Analyzing specifically the TT-12.5, which among the TT connectors is the one with the closest cross-section to the S-19.0, it appears that despite having a 13.43% smaller cross-section, it showed the ultimate load 55.77% higher than stud bolt. However, it is observed that the materials that make up the stud bolt and the tested TT connectors have different properties, being possible a source of the superiority of the shear resistance of the TT connectors. The characterization of the constituent steel of the TT-12.5 indicated a yield stress of 595.3 MPa and an ultimate stress of 716.6 MPa, values higher than the yield and ultimate stresses of the constituent steel of the stud bolt, respectively.

With the proposed finite element model validated, a numerical simulation of the push-out test with TT connectors TT-12.5 was performed, having the same properties as stud bolt steel (f_y = 345 MPa and f_u = 415 MPa), allowing a faithful comparison between the shear resistance of the connectors. The concrete properties have not been modified. The result of the numerical simulation, together with the experimental results of the TT-12.5 and stud bolt connectors can be seen in Fig. 5 and Tab. 2.

Table 1. Ultimate load/cross-section ratios obtained by experimental push-out (Barbosa [6])

Connector	Diameter (mm)	Ultimate load (kN)	Average ultimate load (kN)	Cross section (cm²)	Average ultimate load/Cross section
S-19-1		115.10			
S-19-2	19.0	126.28	124.63	2.84	43.88
S-19-3		132.50			
TT-8.0-1		73.10			
TT-8.0-2	8.0	75.13	74.72	1.01*	73.98
TT-8.0-3		75.93			
TT-10.0-1		112.13			
TT-10.0-2	10.0	122.10	115.19	1.57*	73.37
TT-10.0-3		111.35			
TT-12.5-1		193.58			
TT-12.5-2	12.5	192.60	194.14	2.45*	79.24
TT-12.5-3		196.25			

* sum of the areas of the two legs of the TT connector

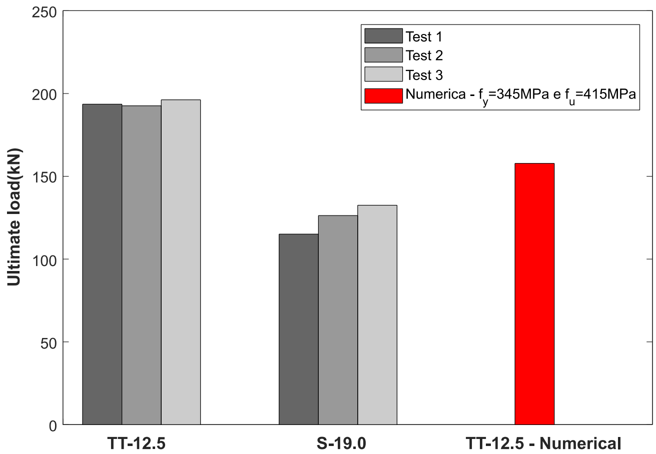

Figure 5. Results of ultimate load experimental of connectors TT-12.5 and S-19.0 and numerical simulation of TT-12.5

Table 2. Ultimate load and Ultimate load/cross-section ratios obtained by experimental push-out and numerical

Connector	Ultimate load (kN)	Cross section (cm²)	Ultimate load/Cross section (kN)
TT-12.5	194.14*	2.45	79.24
S-19.0	124.63*	2.84	43.88
TT-12.5 - Numerical	157.83	2.45	64.42

* Average ultimate load experimental

The result of the numerical simulation showed that the TT connector made of steel with yield and ultimate stresses equal to that of the stud bolt has an ultimate load and an ultimate load/cross-section ratio higher than the stud bolt, about 27% and 47%, respectively. This indicates that the main responsible for the high values of shear resistance of the TT connector is its geometric configuration, where axial forces are predominant and not only the properties of the steel that constitute it.

This analysis was carried out with the objective of showing the efficiency of the TT connector in relation to the stud bolt, from an authentic comparison where the mechanical properties of the connectors were identical. However, in practice TT connector making steel (CA-50) is available on the market with a yield stress of at least 500 MPa, providing TT connectors with high values of shear resistance when compared to stud bolts.

5 Conclusions

In this study, a three-dimensional non-linear finite element numerical model was developed with the intent of performing a comparative analysis between the shear resistance of TT connector and stud bolt. The model considers the non-linearity of the concrete and steel of the TT connector, steel beam and reinforcement of the slab. Both the load-slip curves obtained and the rupture modes observed numerically were consistent with experimental results.

The TT connector was developed in order to offer a viable alternative to the use of stud bolt, since it is manufactured with low-cost material (CA-50) and easily found in the civil construction market, moreover, it does not require specific equipment in the process connection to the steel beam (weld). In addition to the economic and constructive advantages of the TT connector in relation to the stud bolt, the TT connector has a higher ratio of ultimate load/cross section. With the finite element three-dimensional nonlinear numerical model, it was found that the TT connector made of steel with the same properties as the stud bold, presents a 47% ultimate load/cross section ratio. This analysis demonstrated that the main responsible for the superiority of the shear resistance of the TT connector in relation to the stud bolt is its geometric configuration, and not the difference between the properties of the constituent materials.

Finally, it is believed that the numerical model developed and the results of this research contributed to a better understanding of the behavior of the TT shear connector, a connector with great potential for application in composite steel-concrete structures.

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