Study of the behavior and resistance of the U shear connector with cold-formed profile

Lívia C. L. Sousa[1], Jerfson M. Lima[1], Gregório S. Vieira[2]

[1]*Federal University of Ceará, 62900-000, Ceará, Russas*
liacristina2002@alu.ufc.br, jerfson.lima@ufc.br
[2]*Federal University of Uberlândia, 38408-144, Minas Gerais, Uberlândia*
gregorio.eng@gmail.com

Abstract. The use of composite beams leads to economical solutions for use in building and bridge structures, for example, due to the combined action between the steel beam and the concrete slab, providing greater stiffness and flexural resistance than when considering the work isolated from materials. However, as they are two materials with different behaviors, mechanical devices are needed that are capable of ensuring that their elements work together. Such devices are called shear connectors, whose function is to resist the horizontal forces that develop at the steel-concrete interface. The U shear connector made up of a cold-formed profile is a low-cost alternative connector, however, more studies to understand its mechanical behavior need to be developed. The analysis of the mechanical behavior of a shear connector is carried out by carrying out the push-out test, standardized by Eurocode-4 (2004). Another possibility is the use of numerical modeling. In this sense, this work aims to numerically simulate the mechanical behavior of U-shaped shear connectors consisting of a cold-formed profile. The developed numerical model will be calibrated and validated, and applied for a parametric analysis to evaluate the connector resistance.

Keywords: U shear connector, cold-formed profile, push-out test, numerical modeling.

1 Introduction

The use of composite beams leads to economical solutions for the design of structures in large works, such as tall, super tall and mega tall buildings, in addition to their use in bridges and viaducts, as the combined action between the steel beam and the steel slab concrete provides greater rigidity and resistance to bending than when considering the isolated work of these materials. However, mechanical devices called shear connectors are necessary whose function is to resist the horizontal forces that develop at the steel-concrete interface, avoiding the physical separation of these components and ensuring that both materials behave in the same way.

The most used shear connector in Brazil and around the world is the stud bolt. However, the need for high-cost equipment for its installation has made designers rethink its use. As a result, several studies have been carried out in recent years aiming to develop alternative low-cost and easy-to-install shear connectors. One of these connectors studied is the cold-formed U-type shear connector, which despite its efficiency being confirmed in previous studies (SILVA, 2006 [1]; DAVID, 2007 [2]) there is still a need for further investigation into its mechanical behavior.

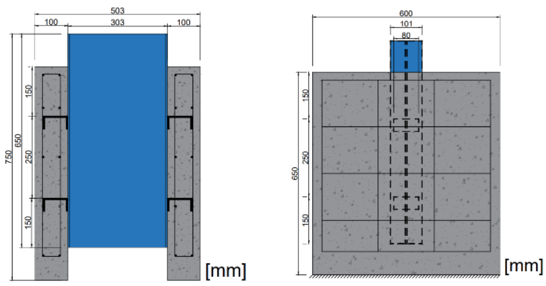
The analysis of the mechanical behavior of a shear connector is carried out by carrying out the push-out test, standardized by Eurocode-4 (2004) [3]. Another possibility is the use of numerical modeling. Numerous researchers have used numerical modeling to study the behavior of shear connectors and obtained satisfactory results (LIMA, et al., 2020 [4], LIMA et al., 2022 [5], BEZERRA et al., 2018 [6]; KIM et al., 2017 [7]; NGUYEN and Kim, 2009 [8]).

Therefore, this work aims to study the resistant capacity of U shear connectors made up of a steel cold-formed profile, evaluating the influence of their height and thickness on the resistance, as well as making a comparison between the resistances obtained through numerical models and the resistance calculated based on the Brazilian standard ABNT NBR 8800:2008 - Design of steel structures and composite steel and concrete structures for buildings [9]. To this end, numerical simulations of the push-out test were carried out, using the ABAQUS software (2014) [10], based on the Finite Element Method (FEM).

2 Push-out test (NETO et al., 2010)

The experimental results of Neto et al. (2020) [11] were used for calibration and validation of the numerical model. Figure 1 shows the geometry of the experimental models

Figure 1. Geometry of experimental push-out models (Neto et al., 2020).



The push-out test consists of supporting the two concrete slabs on a rigid base and applying an increasing load to the cross-section of the steel profile I located between the slabs, making the connectors responsible for transmitting the longitudinal shear efforts between the model components. For more information about the experimental tests, see Neto et al. (2020).

3 Finite Element Method

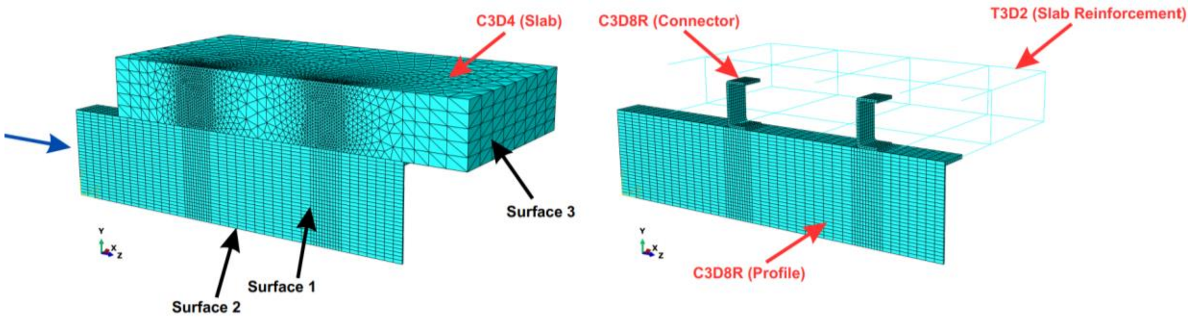
3.1 Geometry

The geometry of the FEM model was based on the experimental push-out models with cold-formed U connector by Neto et al. (2020) (Fig. 1). In order to reduce the computational cost, only a quarter of the model was simulated, taking advantage of the symmetry of the push-out test. For this, symmetry boundary conditions were applied.

3.2 Mesh, finite elements and boundary conditions

The mesh adopted for the FEM model can be seen in Fig. 2. Note that the mesh was composed of 3 types of finite elements available in the ABAQUS library (2014): C3D8R (8-node hexadecimal three-dimensional element with reduced integration), C3D4 (4-node tetrahedral three-dimensional element) and T3D2 (2-node truss three-dimensional element). The connectors and steel profile, as they have regular geometry, were modeled with C3D8R elements. The size of the connector elements was 5 mm. For the steel profile, the element is 25 mm in size in the regions away from the connectors, and 5 mm in the regions of the connector-steel profile connection. In other words, a refinement of the finite element mesh was made in this region, for an adequate simulation of the connection. For the slab, C3D4 elements were used due to the complex geometry in the connector region. The slab reinforcement was modeled with truss elements (T3D2), measuring 5 mm

Figure 2. Finite element mesh and boundary conditions



To prevail the simplification of the model geometry and the simulation of the push-out test boundary conditions were applied. The symmetry boundary conditions consisted of restricting the displacements of the elements on surfaces 1 and 2 in the X and Y directions, respectively. Regarding the boundary conditions of the push-out test, the displacements of surface 3 were restricted in the Z direction. The load was applied uniformly distributed over the cross section of the steel profile. Fig. 2 shows the boundary conditions considered in the model

3.3 Restrictions and contacts

For the interaction between model components, restrictions and contacts were applied. The connector-steel profile and connector-concrete connections were modeled with the Tie type restriction, that is, there is no sliding between the surfaces. Although it is evident that slippage between the surface of the connector and the concrete occurs, this simplification generated satisfactory results. At the interface between the base of the concrete slab and the upper table of the profile, a contact interaction was used. As a characteristic of this contact interaction, a normal hard behavior was adopted (the concrete surface does not penetrate the steel surface and vice versa) and a tangential behavior without friction, so that the shear connectors are responsible for transferring the longitudinal forces between the concrete slab and the steel profile. The slab reinforcement bars were considered embedded in the concrete, with the application of the embedded restriction.

3.4 Analysis method

In this study, the explicit dynamic analysis method was applied. Despite being a dynamic method, it can be applied to the analysis of static models, as long as the inertia effects are controlled with the slow application of load. Several researchers have applied this method to simulate push-out and obtained satisfactory results (LIMA et al., 2020; LIMA et al., 2022; BEZERRA et al., 2018; KIM et al., 2017; NGUYEN and KIM, 2009). In this study, the load application rate was chosen so that during the analysis the effects of inertia were minimal.

3.5 Constitutive models

3.5.1 Concrete

In modeling the concrete, the Concrete Damage Plasticity Model (CDPM) was used, present in the ABAQUS materials library. This constitutive model is suitable for materials that have different tensile and compressive strengths. Furthermore, it links the theory of plasticity with damage mechanics, being able to numerically simulate the degradation of stiffness and failure of concrete. Numerous researchers who numerically simulated the push-out test adopted CDPM as a constitutive model for concrete (LIMA et al., 2020; LIMA et al., 2022; BEZERRA et al., 2018; KIM et al., 2017; NGUYEN and KIM, 2009; QURESHI and LAM, 2012). To use this model to simulate the behavior of concrete, the software requires as input data the plastic parameters, the uniaxial stress x strain curves of concrete compression and tension. Table 1 presents the plastic parameters of the CDPM considered. The uniaxial stress x strain curve of concrete compression was based on the recommendations of the FIB Model Code 2010 [12] and Krätzig and Pölling (2004) [13]. The uniaxial behavior of the tensile was based on the exponential curve derived from the Cornelissen et al. (1986) [14]. For more information on CDPM input data, see Lima et al.

(2020) and Lima et al. (2022). Table 2 presents the concrete properties considered in the FEM model, from the characterization tests by Neto et al. (2020).

Table 1. Plastic parameters of the CDPM

Angle of dilation (φ)	Ration between the magnitudes of deviation stress in uniaxial tension/compression (K_c)	Eccentricity of the plastic potential surface (ϵ)	Ratio between biaxial and uniaxial compressive yield strengths (f_{b0}/f_{c0})
13º	0.7	0.1	1.16

Table 2. Concrete Properties

Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
33.87	3.17	33.40

3.5.2 Steel

In this study, an elastic-plastic constitutive model was used to simulate the cold-formed U connector, steel profile and slab reinforcement. This constitutive model is present in the ABAQUS material library under the name PLASTIC. The PLASTIC model adopts the Von Mises yield criterion, with an associative flow rule, ideal for modeling ductile materials such as steel. The uniaxial behavior implemented in the model consisted of the bi-linear stress-strain relationship for the steel profile and slab reinforcement, and due to its greater importance in the model, the tri-linear relationship was used for the cold-formed U connector. Table 3 presents the steel properties considered in the FEM model, from the characterization tests by Neto et al. (2020).

Table 3. Steel properties

Component	Yield stress (MPa)	Ultimate voltage (MPa)	Ultimate deformation (%)
U shear	235	420	30
connector	411	528	30

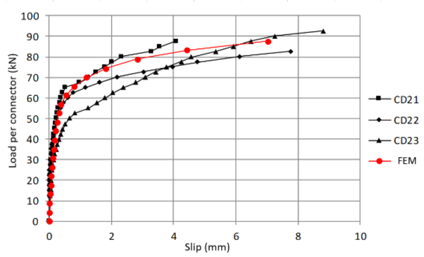
4 Validation of the numerical model

Figure 3 shows the load per connector x slip curves obtained from the push-out tests by Neto et al. (2020) (CD21, CD22 and CD23) and by the FEM model. Table 4 presents in detail the ultimate loads of the cold-formed U connectors obtained by experimental push-out (P_{exp}) and finite element analysis (P_{FEM}). The biggest difference between the experimental and numerical results was 5.68%. These results demonstrate the efficiency of the proposed finite element model in simulating the resistant capacity of cold-formed U connectors

Table 4. Ultimate loads of cold-formed U connectors

Model	P_{exp} (kN)	P_{FEM} (kN)	P_{exp}/P_{FEM}
CD21	87.60		1.000
CD22	82.60	87.57	0.943
CD23	92.50		1.056

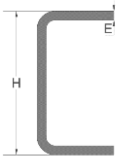
Figure 3. Load per connector x slip curves



5 Parametric study

In this work, in addition to the numerical simulation of the push-out test, the geometric characteristics of the connector, height and thickness were varied, where the length of 80mm was kept constant, as well as the properties of the connector steel and the concrete of the slab. The models were developed with connector heights of 50, 75, 100 and 125 mm, where thicknesses of 3.35, 3.75 and 4.75 mm were adopted for heights of 50 and 75 mm and thicknesses of 3.35, 3 .75, 4.75 and 6.30mm for heights of 100 and 125mm, totaling fourteen numerical models. Figure 4 shows the geometric characteristics that were evaluated

Figure 4. Analyzed characteristics of the cold-formed U shear connector



From the models, the load x slip curve and ultimate load of each connector (Q_{FEM}) were obtained, making it possible to evaluate the influence of the height and thickness of the connector on the resistance. The results of this analysis are described below

5.1 Influence of connector thickness

Figure 5 and Tab. 5 show the ultimate load (Q_{FEM}) of each numerical model simulated considering the variation in connector thickness.

Figure 5. Variation in the ultimate load considering the variation in connector thickness

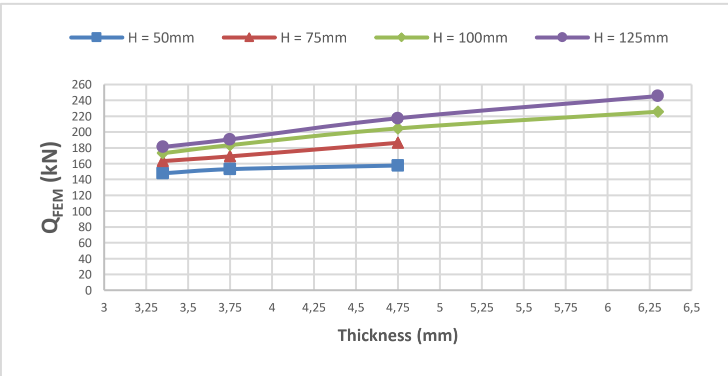


Table 5. Ultimate loads of cold-formed U connectors with varying connector height

Height (mm)	Thickness (mm)	Q_{FEM} (kN)
50	3.35	147.7594
	3.75	153.0365
	4.75	157.654
75	3.35	163.2609
	3.75	169.1977
	4.75	186.3483
	3.35	173.1555

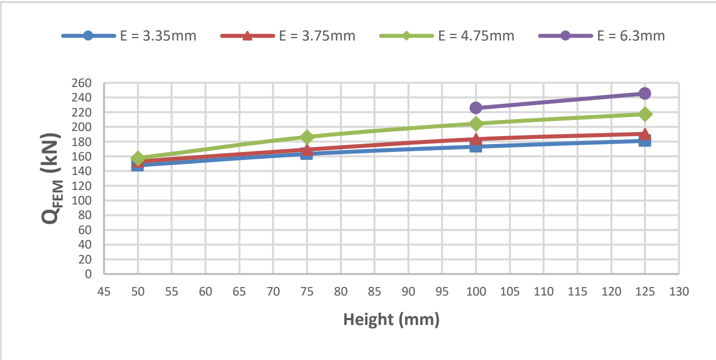
100	3.75	183.3799
	4.75	204.4884
	6.3	225.5969
125	3.35	181.0712
	3.75	190.636
	4.75	217.3514
	6.3	245.3861

As shown in Fig. 5, the ultimate load of the connector increases as the thickness increases, however this gain is only significant for greater heights, since for a height of 50mm, there was an increase in resistance of 6.28%, however, for the same thickness variation, the resistance gain of the 75mm high connector becomes 12.38%, approximately twice the resistance gain for a 25mm height variation. For greater heights, 100 and 125mm, the resistance gain is, respectively, 15.32 and 16.69%. The results obtained numerically reinforce what was presented by DAVID (2007) regarding thickness being an important variable.

5.2 Influence of connector height

Figure 6 and Tab. 6 show the ultimate load (Q_{FEM}) of each simulated numerical model considering the connector height variation.

Figure 6. Variation in the ultimate load considering the variation in connector height



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4.75	50	157,654
	75	186,3483
	100	204,4884
	125	217,3514
6.3	100	225,5969
	125	245,3861

As shown in Fig. 6, the greater the height, the greater the connector's ultimate load, and the greater the thickness, the greater the influence of height variation on the connector's resistance, since for thicknesses of 3.35 and 3.75mm, the gains in resistance were similar to each other, being 18.40 and 19.72% respectively. However, for the thickness of 4.75, there was an increase in resistance of 27.47%, which represents a further value in relation to the first two thicknesses. Therefore, as pointed out by DAVID (2007) through experimental tests, the height of the connector is a geometric parameter with less participation in the increase in connector resistance, since there is only a considerable increase for thicknesses from 4.75mm onwards.

6 Comparison with standards

The resistance of a laminated U profile shear connector, with a cross-sectional height equal to or greater than 75 mm, completely embedded in a solid concrete slab with a flat bottom face and directly supported on the steel beam, is given by:

$$Q_r = 0{,}3\left(t_{fcs} + 0{,}5t_{wcs}\right)L_{cs}\sqrt{f_{ck}E_c} \tag{1}$$

Where

t_{fcs} is the thickness of the connector flange, taken halfway between the free edge and the adjacent face of the web;

t_{wcs} is the thickness of the connector core;

L_{cs} is the length of the U profile;

f_{ck} is the characteristic compressive strength of concrete;

E_c is the modulus of elasticity of concrete;

Figure 7 and Tab. 7 show the relationship between the ultimate load values obtained by the numerical models and the values obtained through the equation (1), where on the horizontal axis of the graph are the ultimate loads calculated by the equation (Qr) and on the vertical axis, the ultimate loads through the simulations (Q_{FEM}).

The red line shown in the graph represents the ultimate load values through the equation, so all connectors whose ultimate load is above the line have greater resistance than ABNT NBR 8800:2008 presents, showing that the standard oversize such connectors. The points below the line represent connectors whose resistance is lower than that determined by the aforementioned standard, showing that the equation is undersized for these connectors, consequently the standardization is against safety in these cases.

Figure 7. Comparison between the ultimate load obtained with numerical simulation and that obtained by the standard equation.

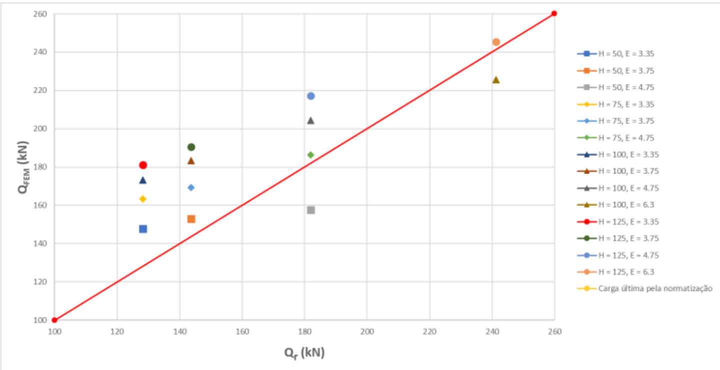

Table 7. Relationship between ultimate loads obtained by FEM and standard matching

Model	Q_{FEM} (kN)	Q_r (kN)	Q_{FEM}/Q_r
H = 50, E = 3.35	147.75936	128.2709	1.151932
H = 50, E = 3.75	153.03648	143.5868	1.065811
H = 50, E = 4.75	157.65396	1818766	0.866818
H = 75, E = 3.35	163.2609	128.2709	1.272782
H = 75, E = 3.75	169.19766	143.5868	1.178365
H = 75, E = 4.75	186.3483	181.8766	1.024586
H = 100, E = 3.35	173.1555	128.2709	1.34992
H = 100, E = 3.75	183.37992	143.5868	1.277136
H = 100, E = 4.75	204.4884	181.8766	1.124325
H = 100, E = 6.3	225.59688	241.2259	0.93521
H = 125, E = 3.35	181.07118	128.2709	1.411631
H = 125, E = 3.75	190.63596	143.5868	1.32767

H = 125, E = 4.75	217.35138	181.8766	1.195048
H = 125, E = 6.3	245.38608	241.2259	1.017246
Mean			1.157
Standard deviation			0.156

From Fig. 7 it can be seen that most models were above the line shown in the figure, indicating that the resistances of these connectors are in favor of safety. However, models with a height of 50 and 100mm, with thicknesses of, respectively, 4.75 and 6.30mm, are below the red line, indicating that the equation is undersized for these connectors.

7 Conclusions

In this work, push-out numerical models were developed to simulate the mechanical behavior of U shear connectors consisting of a cold-formed profile and evaluate the influence of the height and thickness of the connectors on the resistance. The non-linearity of materials (steel and concrete) and contact were considered. The developed model was validated with the experimental results of Neto et al. (2020). The results obtained indicate that height has less influence on resistance, being considerable for thicknesses from 4.75mm, and that thickness has greater relevance for increasing resistance in the connector. The results were consistent with what was studied by DAVID (2007), which shows the efficiency of the numerical models. Furthermore, the ultimate load values obtained by numerical simulation were compared with the values obtained using the NBR 8800 equation, where the lack of adjustment of the equation was highlighted. In this way, the influence of other parameters can be evaluated on the resistance of this type of connector, such as its length and characteristics of the concrete slab, as well as the proposal for a better adaptation of the equation to the numerical and experimental results already existing in the literature.

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