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BEHAVIOR OF STEEL-CONCRETE COMPOSITE BEAMS WITH FLEXIBLE SHEAR CONNECTORS

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Keywords: composite beam, flexible shear connector, cold-formed section, experimental analysis.

***Abstract**. The strength and the stiffness of the connection between concrete slab and steel profile in composite beams depend basically on the number of shear connectors encased in the concrete and their properties. In the case of flexible shear connectors the contribution of friction between the slab and the steel profile may be relevant for serviceability limit states and also for ultimate limit states, provided that the beam span is relatively short and the slab stiffness is relatively large compared to that of the steel profile alone. These conclusions were drawn from previous analytical and numerical models allowing for the shear connectors' flexibility and friction between the slab and the steel profile. The main proposal of this paper is to present the results obtained from experimental tests carried on composite beams with flexible connectors with and without friction contribution. It is shown that the results of all tests validate the conclusions obtained by the analytical and numerical approaches.*

1 INTRODUCTION

The use of cold-formed profile (CFP) in Brazil's construction industry is increasing not only for applications on secondary members such as purlins and space covering members for roofs and walls but also on primary components, for example building floor beams. Figure 1 shows a composite beam cross section in which the steel section is composed of a box CFP and the slab is also a composite member formed by the profile sheeting and concrete (steel deck with ribs perpendicular to the steel box profile).

Aiming to avoid the application of welded shear connectors to the thin-walled CFP, a new detail of shear connector was proposed [1] as illustrated in Figure 2. This shear connector consists of a rivet with internal thread driven in the plate hole and a high-strength bolt. Due to plate bearing deformation (and hole ovalization) this shear connection is much more flexible than a conventional connection with welded shear connector, yielding to particular issues in the composite beam behavior. One of these particular issues is the role played by friction at the interface between the steel profile and the slab which motivated a series of analytical, numerical and experimental studies developed at Federal University of Minas Gerais, Brazil.

The strength and the stiffness of the connection between concrete slab and steel profile in composite beams depend basically on the number of shear connectors encased in concrete and their properties. In the case of flexible shear connectors the contribution of friction between the slab and the steel profile may be relevant for serviceability limit states and also for ultimate limit states, provided that the beam span is relatively short and the slab stiffness is relatively large compared to that of the steel profile alone. These conclusions were drawn from previous analytical and numerical models allowing for the shear connectors' flexibility and friction between the slab and the steel profile [2], [3],[4]. Results from these models did not show good correlation with the provisions of the Brazilian and American Standards which recognize the friction contribution in the behavior of composite slabs [5] -[6] but not of composite beams.

The main proposal of this paper is to present the results obtained from experimental tests carried on composite beams with flexible connectors with and without friction contribution. To remove the friction, a teflon plate was placed at the interface between the steel profile and the slab. It is shown that the experimental results validate the conclusions obtained by the analytical and numerical approaches and that not only the connector strength but also the connector stiffness should be taken into account particularly for deflection evaluation.

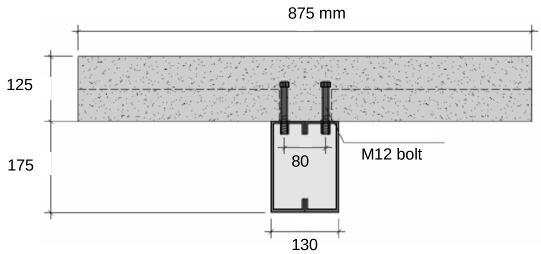
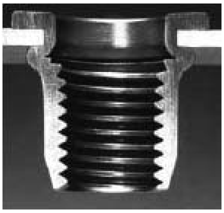


Figure 1: Composite beam cross section showing the box cold-formed profile (CFP), the steel deck slab with ribs perpendicular to the steel section and the shear connectors.

(a)



(b)

Figure 2: Shear connector. (a) high-strength bolt. (b) rivet with internal thread.

2 ANALYTICAL APPROACH – ELASTIC DOMAIN

The fundamentals of the developed analytical approach are briefly presented herein [3]. Although other researchers [7],[8] have already developed analytical approaches for this kind of problem, they did not allow for friction at the interface. Figure 3 shows the analytical model of the composite beam and its components, concrete slab, steel profile and shear connectors which are assumed to behave linear elastically. It is considered that slip may occur at the slab – steel profile interface while vertical separation between these components is restrained.

Free-body diagrams of infinitesimal length elements of the slab and the steel profile are illustrated in Figure 4 where the contact compressive force q_i and the shear flow dF act at the interface between the slab and the steel profile. If the available friction force per unit length μq_i (μ being the static friction coefficient) is greater than the elastic shear flow at the interface then no slip occurs and dF is equal to the elastic shear flow. Conversely, if slip occurs dF is equal to the friction force plus the shear force carried by the shear connectors. The shear flow dF is then given by the following equations:

$$dF = ks + q_i\,\mu\,, \qquad \text{if} \quad q_i\mu < V\,Q_{tr}/I_{tr} \tag{1a}$$

$$dF = \left(V\,Q_{tr}/I_{tr}\right)dx, \qquad \text{if } q_i\mu \geq V\,Q_{tr}/I_{tr} \tag{1b}$$

where Q_{tr} is the first order moment of the slab section in relation to the neutral axis, calculated for the transformed section; I_{tr} is the inertia moment of the transformed section; k is the stiffness of the shear connectors per unit length and s is the slip.

The components s_1 and s_2 of the slip s, associated to the section rotation and to the length variations of neutral axes, respectively, are shown in Figures 4b and 4c. The total slip s at any section is obtained by applying compatibility equations between the displacements of the neutral axis of both the slab and the steel profile due to section rotation (see Fig. 4c) and between the axial deformations of both components as shown in Fig.4b.

Applying the equilibrium equations to the infinitesimal element (Fig. 4a) and the displacement compatibility equations yields to the establishment of two differential equations that govern the problem, one valid for sections where there is no slip and another referred to sections where slip occurs at the interface between slab and steel profile. Solutions of these equations can be found for particular cases, for example for uniform distributed loads q_L and q_P [3].

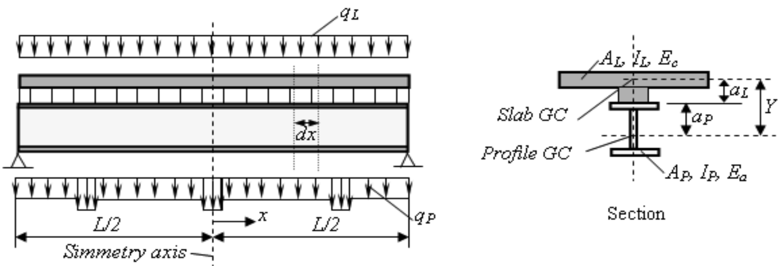
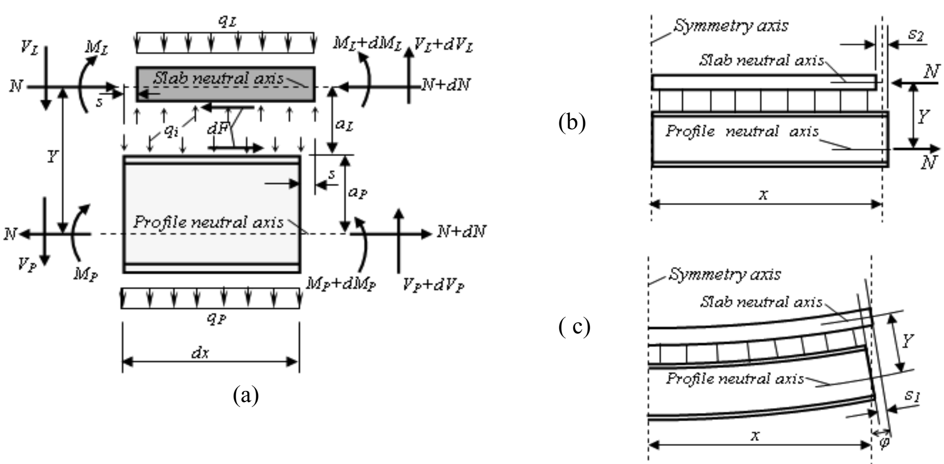


Figure 3: Composite beam and loads.



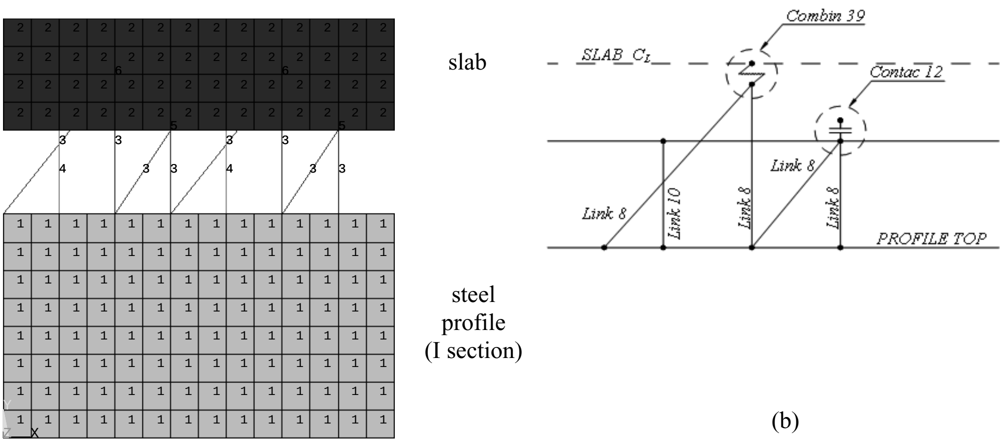
Figures 4: (a) Free body diagrams of the slab and the steel profile. (b) and (c) slip components.

3 NUMERICAL APPROACH

3.1 Finite element model description

A finite element model was developed allowing elastic and plastic analyses of simple continuous composite beams, including friction at the interface, with any type of loading applied to the slab or to the I section profile. The software ANSYS version 11.0 [9], and the following elements were used (Figures 5):

1. Shell 181 – used to model the steel profile and the concrete slab, with von Mises criteria, multilinear stress-strain relation and kinematic hardening;
2. Link 8 – auxiliary elements used to model the shear connector spring at the slab center level ;
3. Link 10 – tension resistant only, used to avoid vertical separation between slab and steel profile;
4. Contac 12 – used to model the friction at the interface between slab and steel profile;
5. Combin 39 – nonlinear spring element used to model the load-slip curve of the shear connectors.



(a) (b)

Figures 5: Finite element model. (a) Basic model. (b) detail of the interface elements.

3.2 Parametric analysis results

Queiroz *at al.* [3] used 8 simple beam models to perform a parametric analysis with the following parameters: (i) span length varying from 3.5m to 7m; (ii) shear stiffness of the shear connectors (one with usual stiffness and another very flexible); (ii) with and without friction at the interface between the slab and the steel profile. Theoretical analyses were carried out with the aid of the analytical approach described in section 2 and the numerical model presented in section 3. The main conclusions of this study may be summarized as follows:

a) A good agreement was achieved between analytical and numerical results.
b) The contribution of friction to the shear stiffness at the slab – steel profile connection is increased with the flexibility of the shear connectors.
c) The influence of friction to ultimate limit state is relevant in cases of short spans, flexible connectors and relatively large stiffness of the slab toward the steel profile one.
d) The effect of friction in vertical displacements appeared in all studied cases, being more prominent in the situations described in (c).
e) The flexibility of the shear connectors should be included in the expressions given by Brazilian [5] and North-American [6] codes to calculate composite beam deflections.

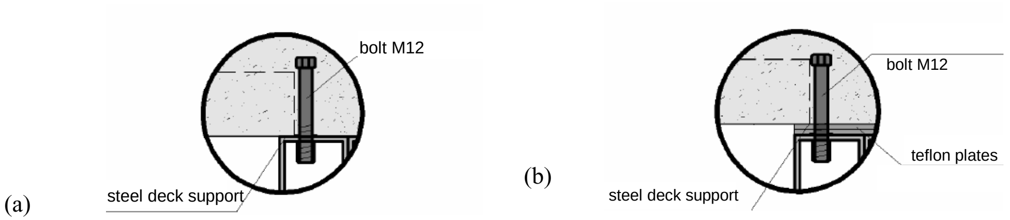
4 EXPERIMENTAL ANALYSIS

4.1 Models description

Aiming to verify the relevant role played by friction at the interface slab – steel profile in the composite beam behavior the models for the experimental analysis were conceived on the basis of the conclusions drawn from the parametric study with the following characteristics: short span equal to 3.5m and flexible shear connectors.

The beam model cross-section is illustrated in Fig.1. The box section profile is formed from a 2mm thick SAC300 steel plate (f_y=300MPa). The slab is composed of 20MPa compressive strength concrete casted on steel deck with ribs perpendicular to the steel profile.

Two series of models were tested, each one with two models totalizing four tests. The models named F1 and F2 refer to beams with friction at the interface between slab and steel profile and the models **N**F1 and NF2 had no friction contribution. Figures 6 show the seldom difference between the two series: the placement of teflon plates at the slab-steel profile interface in order to remove friction.



Figures 6: Details of the slab-steel profile interface. (a) models F1 and F2 with friction. (b) models NF1 and NF2 without friction.

The shear connectors (Figs. 2) were made of high-strength bolts with 12mm diameter (DIN 960 class 5.8 steel) and SAE 1040 rivets. Push-out tests performed in a similar composite beam with these shear connectors and steel deck ribs parallel to the steel profile yielded the average load slip curve illustrated in Figure 7 from which one can calculate the initial stiffness associated to one connector equal to 70 kN/cm. It is indeed a very flexible connector leading to partial interaction behavior of the composite beam. The low stiffness is due to bearing deformation of the 2mm thick plate (and consequent hole ovalization).

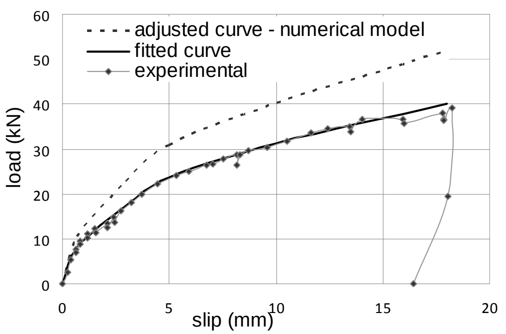


Figure 7: Load slip curves of the shear connection associated to one connector. The curve fitted to the experimental points [1] was adjusted to be used in the numerical model (see Section 5).

The beam was designed for full connection (governed by steel strength) resulting in 22 connectors almost uniformly distributed along each side of midspan section.

The beam models were subjected to four concentrated forces in order to simulate a uniform loading. Figure 8 shows the test setup and the models instrumentation which consists of displacement transducers

(DT) at midspan and also at the beam ends to measure end slips, and several strain gages (EER) along the beam height at midspan section.

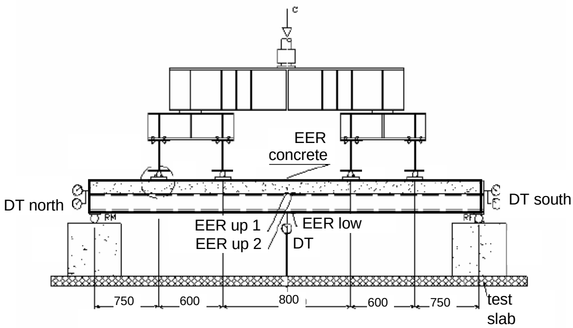


Figure 8 : Setup for experimental tests and model instrumentation.

4.2 Experimental results

Figure 9 presents the beam responses in terms of bending moment *x* deflection at midspan section for all four tested models. It can be clearly observed the favorable influence of friction to the beam stiffness and resistance. Collapse loads and bending moments can be found in Table 1 where it is shown that the ratio between the average collapse bending moments of the beams with friction and without friction achieved 1.16. This result was obtained for painted surface of the profiles and thus higher values are expected for untreated surface. Defining the service bending moment as the one associated to the limit deflection equal to L/300 it can be noticed in Figure 9 that this moment corresponds to 46 kNm for the beam with friction and to 40 kNm to beam without friction, a difference of 11% assigned to the favorable effect of friction.

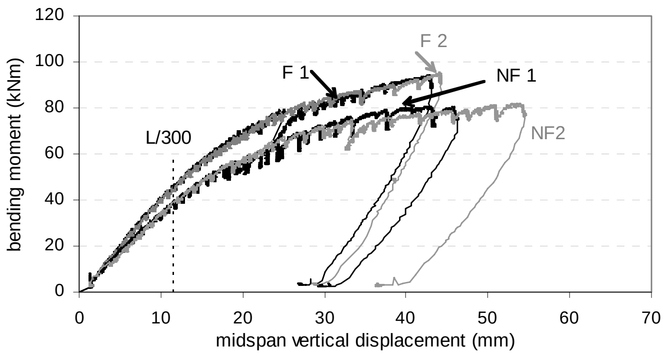


Figure 9: Bending moment deflection curves for the four models tested.

Figure 10 presents the bending moment end slip curves measured at both ends of models F2 and NF1 by displacement transducers (see Fig. 8). For the model with friction (F2) maximum end slip is 2mm while the model without friction attained 4mm end slip. From Figure 7 it is seen that the connectors in the beam with friction, unlike the connectors in the NF1 model, maintain their initial stiffness almost until the beam collapse.

Table 1: Collapse load and bending moment

Model	Collapse load (kN)	Collapse bending moment Mc (kNm)	Average Mc	With friction / Without friction
F1	174.2	94.3		
F2	176.2	95.4	94.8	1.16
NF1	148.4	80.8		
NF2	151.1	82.2	81.5	

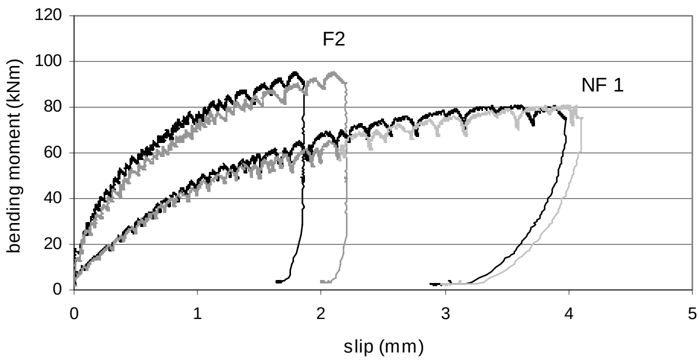
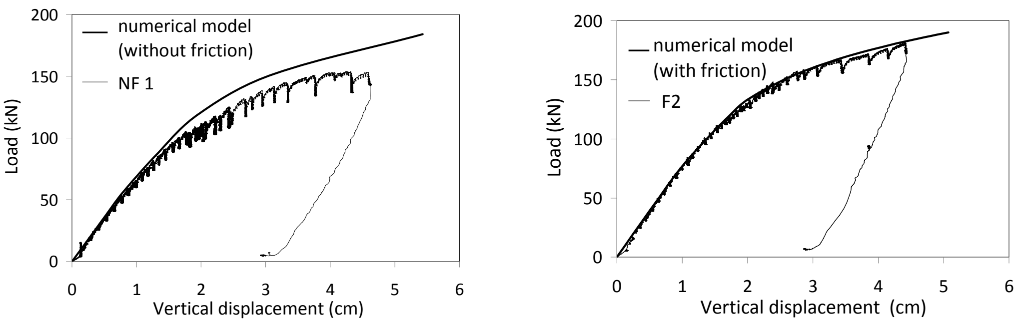


Figure 10: Bending moment *x* end slip curves for models F2 (with friction) and NF1 (without friction).

5 COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

The models of series F and NF tested at the laboratory were simulated with the finite element model described in section 3. For that purpose the CFP box section was transformed to an equivalent I shape. Figure 7 shows the connectors load slip curve adopted in the numerical model. The curve fitted to the experimental results was further adjusted to consider the lower number of shear connectors of the numerical model in each beam side (17 connectors) as compared to the physical model (22 connectors).



(a)

Figures 11: Comparison between numerical and experimental results. (a) model without friction. (b) model with friction.

The comparisons between numerical and experimental results can be appreciated in Figures 11 *a* and *b* respectively for the beam models NF (no friction) and F (with friction). A very good correlation was achieved throughout the loading stages for the beam with friction taken into account. The behavior of the beam without friction was very well simulated by the numerical model for loading stages until half collapse load approximately, after which experimental stiffness degradation took place due to concrete cracking in the tension area. The behavior of the concrete after cracking was not considered in the numerical model.

6 CONCLUSIONS

The results of experimental tests in simple composite beams showed that friction at the interface between the slab and the steel profile plays an important role in the behavior of short span beams with flexible connectors. For the 3.5m span tested beams with connectors composed by bolts threaded to rivets a 16% increase in collapse bending moment was assigned to friction favorable effect. It is important to notice that the friction influence is reduced when part of the slab vertical reaction is supported by a transverse beam. As the experimental tests of composite beams are usually made without this additional support researchers should be aware of this difference. It also became evident that not only the connector strength but also the connector stiffness should be considered in the design, specifically in deflection evaluation.

The numerical model developed to simulate the tested beams behavior was validated through a very good correlation achieved in regard to the experimental results particularly in the case where friction is taken into account.

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INFLUENCE OF THE FRICTION AT THE SUPPORT IN THE LONGITUDINAL SHEAR STRENGHT OF COMPOSITE SLAB

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Keywords: composite slabs; partial shear connection method, friction at the support.

***Abstract**. The aim of this work is to evaluate the behavior and strength of composite slabs considering the influence of the friction at the supports. For this, were used the results of a program of laboratory tests carried through in the Structural Engineering Department of UFMG, considering the Steel Deck-60, which consists of trapezoidal profile with embossments in "V" shape. During the tests deflections, end slips and strains of the steel decks were measured, allowing the analysis of the behavior of the composite slab system and the determination of its failure mode. The influence of the friction at the supports in the longitudinal shear bond was evaluated through the partial shear connection method, using the friction coefficient recommended by [1]. Comparative analysis with other methods allow affirming that the influence of the friction at the support in the longitudinal shear bond is significant, mainly, in composite slabs with short shear spans.*

1 INTRODUCTION

Composite slab systems have prevailed as an appropriate method for building slabs. From the standpoint of the structural behavior, the profiled steel sheet shall be capable of transmitting horizontal shear at the interface between the sheet and the concrete. Composite behavior between profiled sheeting and concrete shall be ensured by mechanical interlock provided by embossments, frictional interlock for profiles shaped in a re-entrant form, end anchorage provided by welded studs and friction of the region of the supports. If there is no mechanical link or an attachment by friction between the sheeting and concrete, it will not be able to transmit the longitudinal shear, and thus the composite slab action will not be effective.

The aim of this paper is to present the partial shear connection method considering the influence of friction at the support for determining the additional longitudinal shear resistance of composite slab system *Deck-60*, after curing the concrete. To achieve this goal the results of research carried out by [2] were used.

2 CHARACTERIZATION OF THE SPECIMENS AND TEST PROCEDURE

To develop the analysis by the partial shear connection method considering the friction at the support, a series of twelve specimens of the *Deck-60* with simple support was tested to bending. The models were divided into two groups, six with nominal thickness t = 0.80 mm and six with t = 0.95 mm. The steel deckings of the specimens were made of steel ZAR 280 and ZAR 345 for thicknesses t = 0.80 mm and t = 0.95 mm, respectively, and length L = 2500 mm and nominal width b = 860 mm. In each group three specimens had depth h_t = 110 mm and span shear L_s = 800 mm and the other three specimens had depth