ANALYSIS ON THE BEHAVIOUR OF COMPOSITE SLABS UNDER CONCENTRATED LOADS.

EXPERIMENTAL TESTS AND NUMERICAL SIMULATIONS.

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SUMMARY

The present study pretends to evaluate the behavior of composite slabs with profiled steel sheet under concentrated loads, reproducing the effect of vehicles and special equipments. To this kind of structural elements are related a characteristic failure mode, the longitudinal shear, beyond usual failure mode considered for slabs. The connection between concrete and steel sheet is assured by friction and mechanical interlock provided by the embossments of the steel deck, both guarantee resistance to longitudinal shear. This shear-bond is a complex phenomenon to reproduce in finite element models and also in the definition of experimental programs. The study was based on experimental tests of two continuous slabs until failure and a pull-out test, which took place in the Laboratório de Estruturas e de Resistência dos Materiais (LEBM) of the Instituto Superior Técnico, and were developed finite element models in ADINA®. Analyzing the interaction between punching shear and longitudinal shear was possible to establish a standard behavior according to the failure mode and the models developed achieved conservative values and nearly the experimental values.

The research was concluded with comparisons between the previous results and the semi-theoretical values from the Eurocodes, obtaining values in good agreement with experimental tests governed by punching shear and conservative values for experimental tests conditioned by longitudinal shear.

Key-words: composite slabs; Eurocodes; experimental tests; longitudinal shear; pull-out; punching shear;

1. INTRODUCTION

1.1 State of the art

The merits of using profiled steel sheeting composite floors have been recognized for its efficiencies in construction, combining the functions of formwork, platform of work while construction phase and reinforcement for sagging moments. The shear-bond resistance is essential to the interaction between steel sheeting and concrete at the sheet-concrete interface, and governs the composite slab design in most cases.

Current design methods found in standards and guide lines rely on the results of costly and time-consuming large-scale laboratory tests. Two new approaches have been developed to replace those kinds of tests, based on small scale test, known by slip-block test and pull-out test, both try to determine the value of longitudinal shear strength. Crisinel developed a new approach for the pull-out test that combines the results from standard materials tests and small-scale tests with a simple calculation model to obtain the moment-curvature at the critical cross-section of a composite slab [Crisinel, 2004]. Another research field relies on finite element models to predict the behavior of the composite slabs preventing the large scale tests.

In order to study the shear-bond action in composite slabs Chen [Chen, 2003] tested seven simply supported one-span composite slabs and two continuous composite slabs using different end restraints in the simply supported slabs concluding that shear-bond governs the resistance in composite slabs, no matter the boundary conditions of the slab.

Other studies were carried out to evaluate the shear-bond action in composite slabs and to compare the results obtained for both methods available in Eurocode 4 for the ultimate limit state of longitudinal shear, concluding that the longitudinal shear carrying capacities calculated by m–k method and partial shear connection method differ by about 26% in the average [Marimuthu, 2007].

2. EXPERIMENTAL PROGRAM

2.1 Pull-out test

The pull-out test was developed under the pre-defined measures, such as the concrete length with 300 mm and the high of the concrete above ribs as 100 mm maximum**.** The two ribs of the profiled steel sheet, who suffered no special treatment, were bolted to a central flat sheet so the machine of universal tests Instrom could pull the ribs out of the concrete layer. The self-weight of the concrete was simulated by the pre-stressed bolts on the side of the specimen (Figure 1). The relationship between the strength and the displacement, constantly throw time, measured by the machine of universal tests Instrom is shown in the Figure 3, where the behave of this type of profiled sheeting may be classified as ductile. Local crushing of the concrete near the embossments and transversal movements of the steel sheet led to final slip.

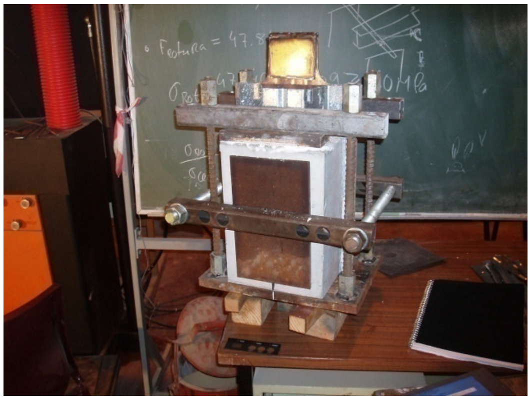

Figure 1- Pre-stressing bolts along the major length of the specimen.

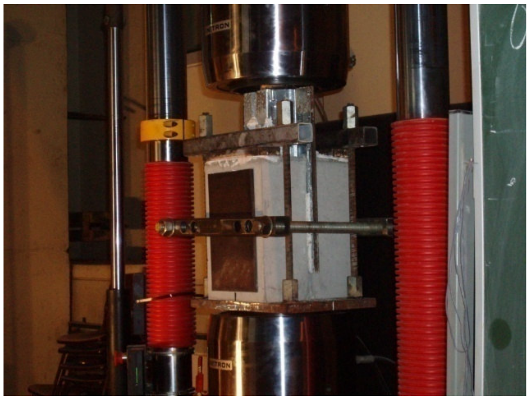

Figure 2 – Slip between concrete and steel sheet during the pull-out test.

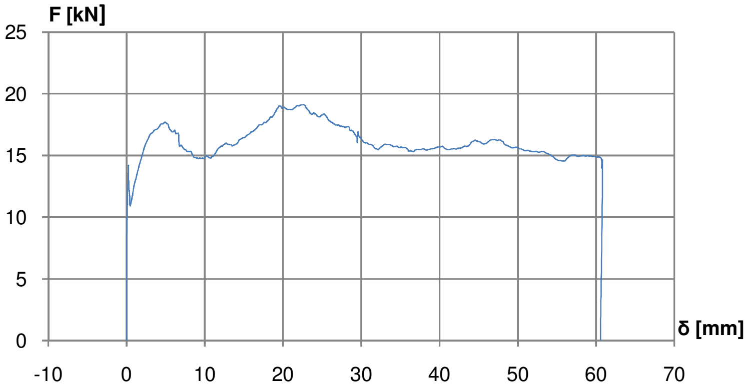

Figure 3 – Force-displacement relationship, usual of ductile composite slabs.

2.2 Preparation of the composite slabs specimens

The intention on studying the effect of punching shear in composite slabs lead to the construction of two identical slabs, with an overall depth of 12 cm, width of 2,3 m and 5 m length divided into 3 spans each measuring 1,5 m, supported by metallic beams with no anchorage. The bottom layer of the composite slabs was 0*,75* mm thick profiled steel sheeting, the strength of which is f_{sy} = 382 MPa. To prevent cracking due to the retraction of concrete was disposed a continuous rebar and over the continuous supports were provided reinforcements to insure hogging bending resistance, according to national norms.

The effect of concentrated loads intent to simulate vehicles and special equipments and for that reason, different areas of contact were used, following the Eurocode 1, [table 6.7 and clause 6.3.3.2 (2), EN 1991-1-1], which states that:

- For vehicles under 30 kN of self-weight, should be used a square area of 100 mm by side;
- For vehicles over 30 kN of self-weight, should be used a square area of 200 mm by side;

Besides these two areas was used an area of 300 mm by side for any other specific case.

Both slabs were provided with the same equipment to measure the vertical displacements along the spans and the relative displacement between concrete and the steel deck on the top of each slab. Strains were also measured along the spans. Following the test procedure, disposed in ANNEX B.2.4 [EN 1994-1-1], all tests begin with 25 cycles between 5% and 40% of the expected failure load and afterwards load increments are imposed such that failure does not occur in less than 15 minutes.

2.3 Experimental results

Were performed 9 experimental tests, by changing the loaded span and the area of contact, and the Table 1 resumes the main characteristic of all experiments and also the failure mechanism observed.

Table 1 – Characteristics and main results for each experimental test.

Experimental test nº	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
100 x 100 mm	√	√	√						
200 x 200 mm				√	√		√	√	
300 x 300 mm						√			√
Midlle span	√	√	√				√		
External span				√	√	√		√	√
Load [kN]	*100*	*100*	*100*	*95*	*84*	*127*	*173*	*120*	*120*
Failure mechanism	*Punching shear*			*Longitudinal shear*					

2.4 Analysis of the experimental results

Combining the results of some experimental tests it was possible to identify a typical behavior according to the failure mechanism and also to analyze the influence caused by each variable. The comparison between tests with the same conditions showed a very similar resistance, as expected, only the displacements were different due to the initial cycled load which in some cases imposed plastic deformations to the composite slab.

The influence of the area of contact used for each test was analyzed by establishing a comparison between the tests with different areas but with the same span loaded. All the cases studied showed that the increasing of the area leads to a higher load, as expected. One of the cases is the comparison between experimental tests nº 2 and 3 (100 x 100 mm) with nº 7 (200 x 200 mm) loaded in the middle span, where the ductile behavior of the experimental test nº 7, due to the longitudinal shear failure, is not so evident, thought both tests with an area of 100 x 100 mm, conditioned by a punching shear failure, present a brittle behavior. Other difference relies on the behavior after the rupture, where the tests with punching shear failure show a ductile capacity given by the profiled steel sheet, not yielded at the point – the reinforcement bars already broke by the punching mechanism – on the other hand the test governed by the longitudinal shear decreases its resistance with the increasing on the vertical displacement.

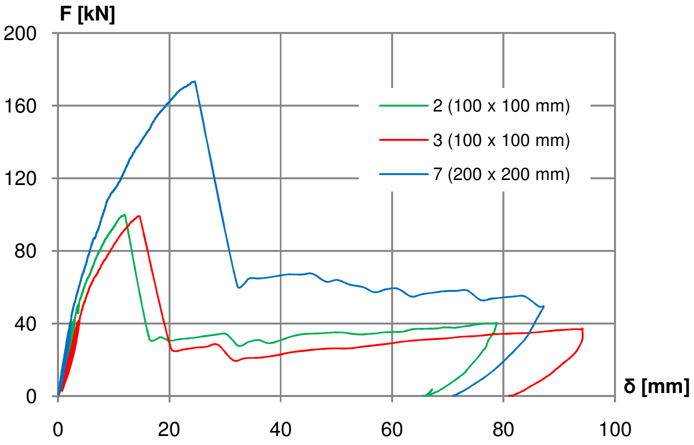

Figure 4 - Force-displacement relationship for experimental tests nº 2,3 and 7.

To evaluate the influence of the position of the load were compared the only two test done with the same area of contact but in different spans, which are the experimental test nº 7 and 8 (Figure 5). Both were conditioned by longitudinal shear failure but between them is noticed that the experimental test nº 8, with the external span loaded, has less resistance and a more brittle behavior until rupture happens.

Figure 5 – Force-displacement relationship for experimental tests nº 7 e 8.

3. FINITE ELEMENTAL MODELS

3.1 Introduction

The choice of the finite element program was based on the need of modeling the curved shape of the profiled steel sheet, to analyze the effect of friction and to perform a non linear analysis, and the program ADINA® satisfied all those items. All the materials were defined upon the mechanics properties obtained from the experimental tests and the relationships adopted for each material were: plastic bilinear for reinforcement bars and profiled steel sheets, and for concrete the program has a specific option for this material, considering a non linear relationship for compression and linear for traction.

3.2 Pull-out

The attempt to create a simple model to predict the ultimate load obtained in the pull-out test resulted in the modeling of a shorter specimen, considering only the concrete between two ribs, as shown in Figure 7. All the measures were taken directly from the steel sheet (Figure 6). To insure the steel sheet did not pass throw the concrete, all the transversal displacements were restrained, this simplification meant that the frictional effect, defined by the coefficient of Coulomb, was only due to the self-weight of the concrete – the friction due to the reducing of the cross-section of the steel sheet caused by the Poisson effect was despised. The mechanical interlocking was simulated by linking all the nodes of the finite elements between the steel sheet and the concrete on the curved surfaces of the embossments.

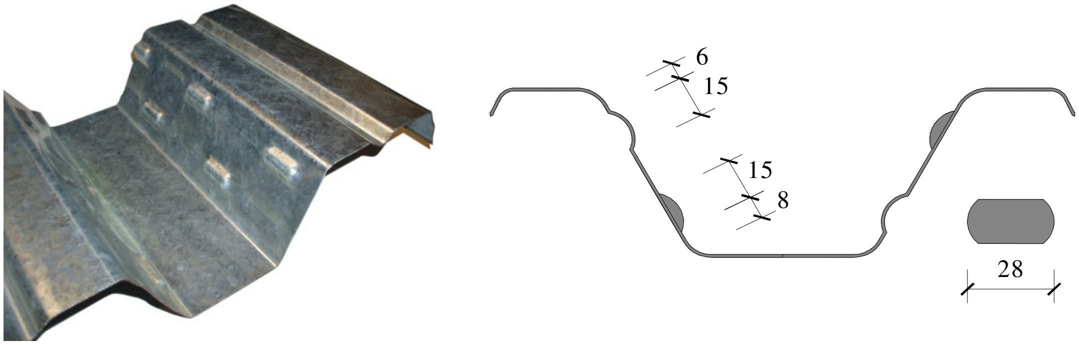

Figure 6 – Measures adopted to model the profiled steel sheet [mm].

The boundary conditions were defined by restraining all the displacements and rotations of the cross sections of the concrete, so that the steel sheet could slip. The load was applied in the contour of the profiled steel sheet as shown in Figure 7. With the intention of validate the whole model, was perform a parametric study with the coefficient of Coulomb, ranging values from 0, oiled surfaced, to 0,5, value stated in Eurocode 4. The results are presented in Figure 8, where the influence of this parameter is noticed, and so, for all the information relying on these results, from now on the value μ = 0,5 will be used.

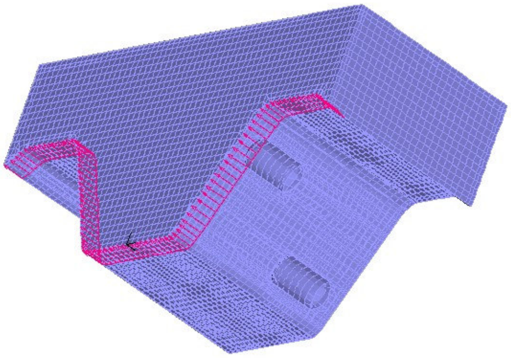

Figure 7 – Load applied on the contour of the profiled steel sheet.

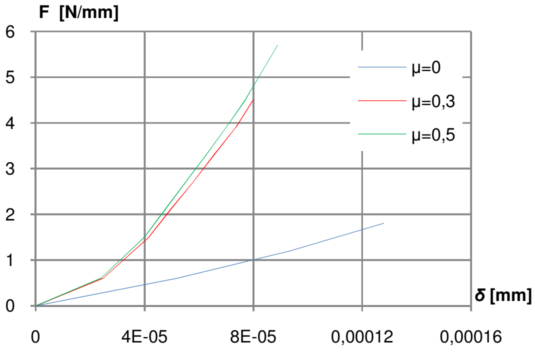

Figure 8 – Force - longitudinal displacement relationship for different values of the parameter μ.

3.3 Model of the composite slab

This model proposes to predict the global behavior of the composite slab, where all the components were modeled, such as the reinforcement bars (Figure 9). However, for an efficient matter, the composite slab was reduced to a simple specimen by using the properties of symmetric structures and all the embossments were replaced by spring elements decreasing the final number of equations needed for the program to solve.

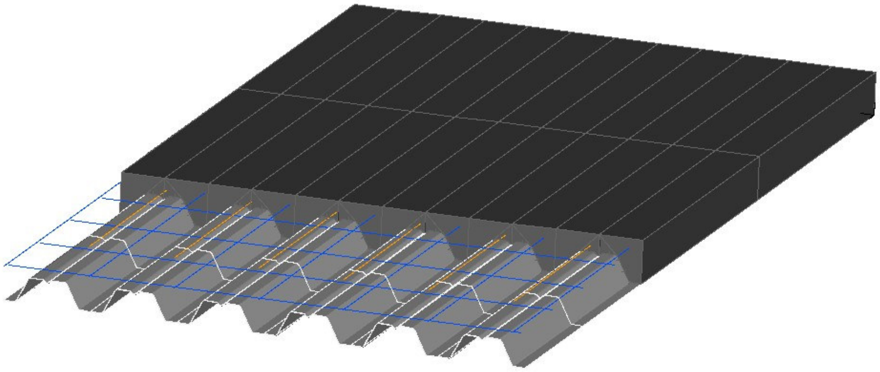

Figure 9 – Model of the composite slab with a continuous rebar (blue) and reinforcement bars over the beams (orange).

Concrete was model by 3D elements of 8 nodes , steel sheet was model by shell elements of 4 nodes and the reinforcement bars and beams were simulated by *Hermitian* 2D elements. The major dimension for any elements was 50 mm. The selection of these elements for each material was forced due to internal demanding of ADINA®, in fact by joining all the options needed and all the boundary conditions the number of nodes for elements ended up limited to this final choice.

The shear-bond strength was calibrated based on a linear regression of the pull-out model results, as shown in Figure 10, and applied proportionally to the length of the composite slab. The stiffness of the spring elements, *K*, was calculated based on the relative displacement measured in the pull-out model between concrete and the profiled steel sheet, and the final value, adapted to composite slab dimension, was 16000 N/mm.

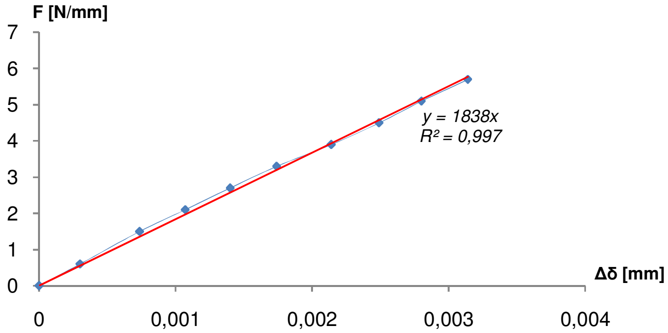

Figure 10 – Linear regression for the force-relative displacement relationship of the pull-out model.

In order to validate the concept of the whole model was performed a parametric study with the value of the stiffness of the spring elements, with K=0, no connection at all, and K=16000 N/mm. The results confirm the expected, achieving a higher resistance the model with K=16000 (Figure 12).

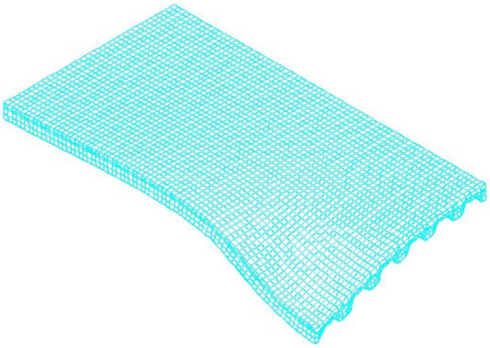

Figure 11 – Amplified deformed shape of the composite slab with an area of contact 200 x 200 mm.

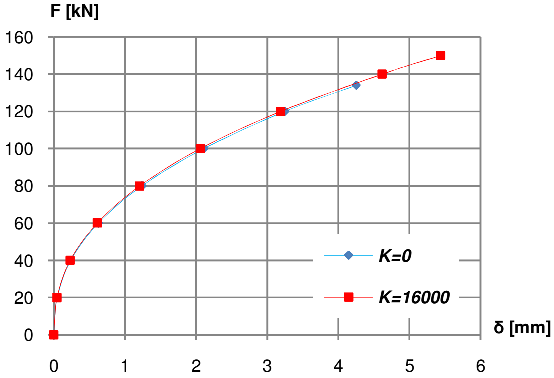

Figure 12 – Force-displacement relationship.

3.4 Simplified model of the composite slab

The concept of this model is to predict the behavior of the composite slabs by a simple and practical model, with no geometry exigencies representing the whole model by a flat geometry, and simulating the shear-bond resistance at the sheet-concrete interface with a material defined for the pull-out experimental results. The normal tension calculated for the instant when the slip occurred, σ =35 MPa, was adopted as the yield tension for the plastic bilinear relationship and the elastic modulus was the steel value, in attempt to express the initial stiffness observed in the Figure 3. Due to internal demanding of ADINA® all the finite elements were the same as for the previous model, with the material at the interface model with shell elements of 4 nodes.

The amplified deformed shape of the composite slab is shown in Figure 13, which able the analysis of the compatibility between all nodes generated. The parametric study in this case was developed for the value of the yield tension, in order to confirm the conception of the model (Figure 14), and for that reason were compared two models with partial connection, f_y=35 MPa and f_y=80 MPa, with a total connection model, concluding that for higher values of the yield tension the model achieved higher resistance.

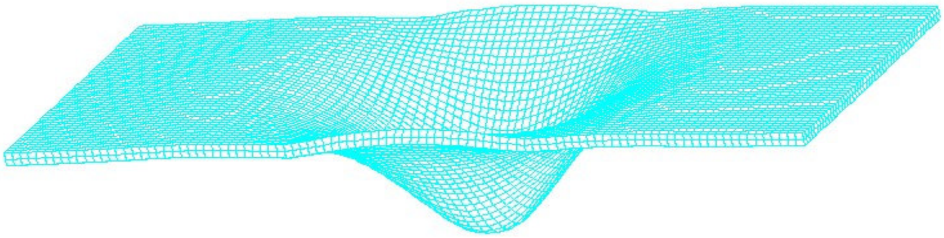

Figure 13 – Amplified deformed shape of the composite slab.

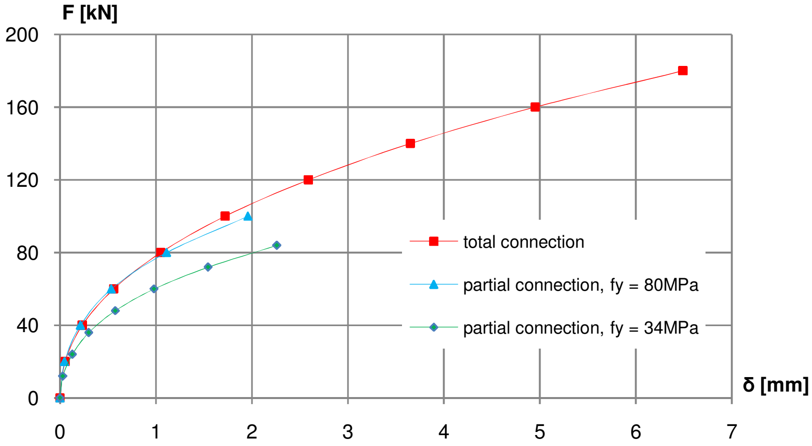

Figure 14 – Comparison between two partial connection models and a total connection model.

3.5 Analysis of the numerical results

Pull-out model

The maximum strength obtained for the pull-out model was 5,7 N/mm and converting that number, so that experimental and numerical values can be compared, proportionally to the pull-out specimen and multiplying for the two ribs the maximum force of the model, F_m, is 11,5 kN which represents 80% of the experimental value, as shown in Figure 15.

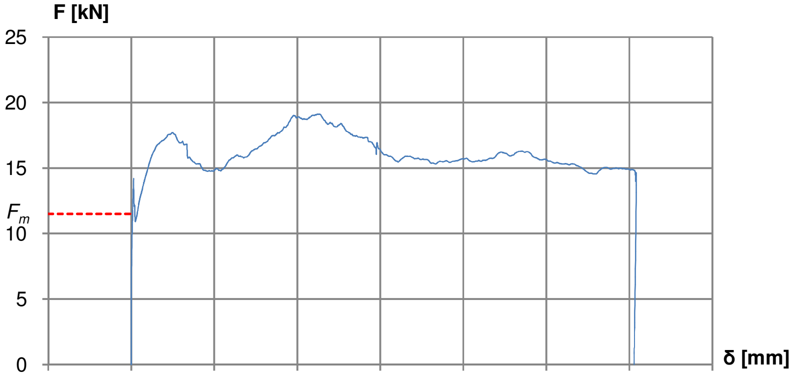

Figure 15 – Force-displacement relationship of the pull-out test with the maximum value obtained by the pull-out model F_m.

Model of composite slab

In terms of resistance this model is a fine tool to predict the ultimate load of the composite slab, as an example, for the area of contact 100 x 100 mm the value obtained was 90% of the experimental value and for 200 x 200 mm case was 87%. In fact the only problem observed in Figure 16 was the stiffness of the model with shorter displacements when comparing to experiments. The main reason may be the shell elements of 4 nodes that can only define linear displacements between nodes.

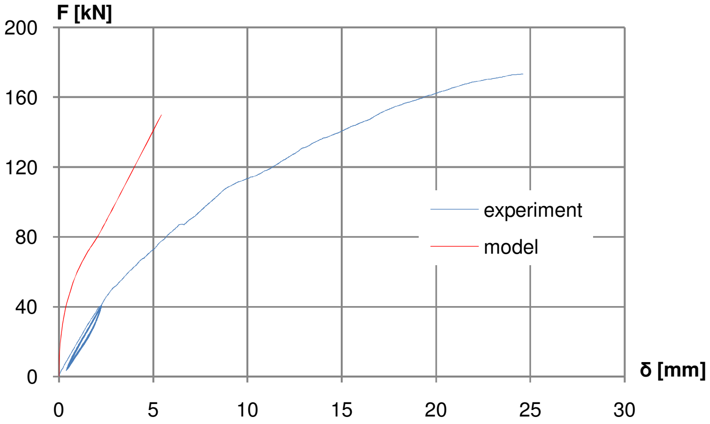

Figure 16 – Comparison between experimental and numerical data.

Simplified model of the composite slab

All tests made with this model, by changing the span loaded and the area of contact, obtained conservative values, the Figure 17 establish the comparison between experimental test nº 7 and the model where the maximum load resulting from the model was 49% of the experimental value.

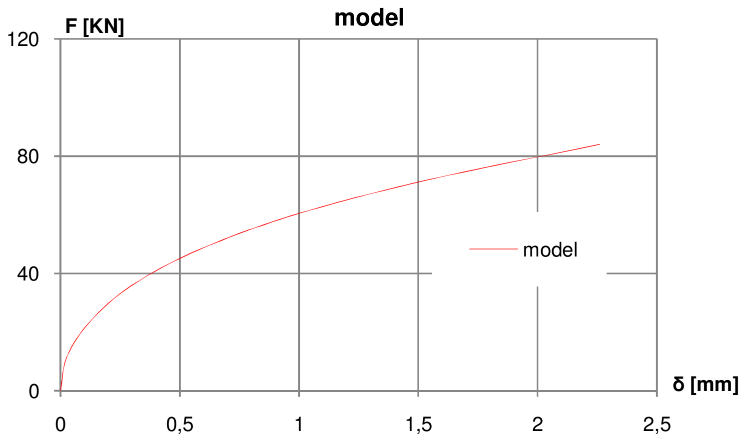

Figure 17 - Comparison between experimental and numerical data.

4 – Analysis of the results according to Eurocodes

After calculating the resistance of the cross section to ultimate limits states for all the failure mechanisms, using medium values for mechanical properties of materials, is possible to analyze the conditional failure mode according to Eurocodes. The evaluation presented next is divided into the conditional failure mechanism observed for each experimental tests and so, in Table 2 are the ultimate loads for all failure modes to the experimental tests nº 1,2 and 3 conditioned by punching shear.

Table 2 – Ultimate load [kN] according Eurocodes for experimental tests nº 1,2 and 3 (* - m-k method).

Flexure	*Vertical shear*	*Punching shear*	*Longitudinal shear (*)*	*Experimental value*
272	*466*	*99*	*125*	*100*

Eurocodes seem to indicate quite well the conditional failure mode and the value for the collapse load, in good agreement with the experimental value for experimental tests governed by punching shear. All the other tests, governed for longitudinal shear, where also well predicted in terms of the conditional failure mode. However the ultimate load differed in average 8 kN when calculated for m-k and partial connection methods, comparing to experiments the semi-theoretical values were not conservative. The analysis should be careful in this matter, in fact the experiments conditioned for longitudinal shear suffered the influence of the previous experiments – it is not like in experiments conditioned by punching shear where the damages on the composite slabs are local. In Table 3 the only experiment that may be compared is the nº 7, which was the only experiment prepared with the slab intact, concluding that the semi-theoretical values were quite conservative.

Table 3 – Comparison between m-k and partial connection methods.

Experimental test nº	*$P_{máx}$ – m-k method [kN]*	*$P_{máx}$ – parcial connection method [kN]*	*P_{real} [kN]*
4	*115*	*128*	*95*
5	*115*	*128*	*84*
6	*124*	*125*	*127*
7	*134*	*142*	*173*
8	*115*	*128*	*120*
9	*124*	*125*	*120*

Simplified method of Crisinel

The proposed New Simplified Method is an attempt to harmonize the longitudinal shear resistance calculations for these two types of composite elements by replacing bending tests of full-scale composite slabs by pull-out shear tests of small scale specimens. The bending resistance of the composite slab is then determined by applying a certain curvature to the critical cross-section until failure of the connection occurs by exceeding the longitudinal shear resistance. Given the shear stress values, obtained by way of pull-out test, and using an Excel spreadsheet for the calculation of the moment-curvature relationship for the given structural system, it was possible to calculate the partial shear connection moment of resistance shown in Figure 18.

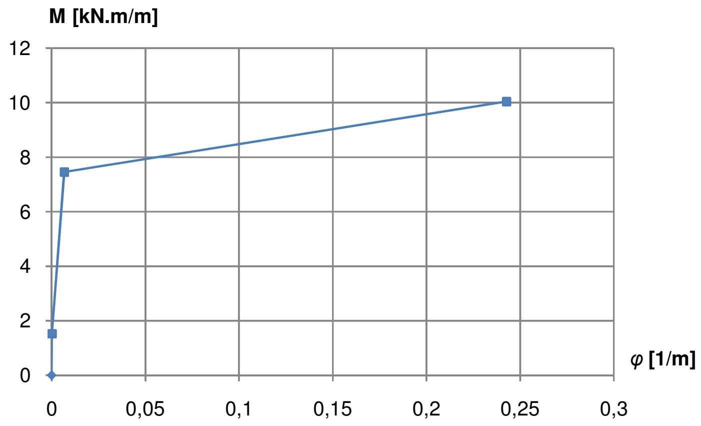

Figure 18 – Simplified moment-curvature relationship.

In the impossibility of reaching the plastic moment due to the longitudinal shear, this method states that the maximum moment possible in the cross-section is 10,5 kN.m/m and comparing with the value calculated according to partial connection method, of 16,7 kN.m/m the method proposed by Crisinel gives a very conservative value.

Effective widths

By the calculation of experimental widths, based on experimental strains converted to stresses and then by the area obtained for a polynomial regression adapted to the 3 points known and divided for the maximum stress value, was finally possible to compare with Eurocode values. In Table 4 are disposable all values corresponding to the half of the ultimate strength for only the last 3 tests, where is possible to conclude that Eurocode values are too conservative.

Table 4 - Experimental and theoretical effective widths.

Experimental test nº	*7*	*8*	*9*
Area of the stress field	*265*	*329*	*331*
b_{eff} [m]	*1,36*	*1,35*	*2,23*
b_{em} (EC 4) [m]	*0,82*	*1,07*	*1,17*

5 - Conclusions

Joining all the information relative to the 3 main points developed, which were the experimental program, the finite element models and the calculus according to Eurocodes, was possible to conclude that:

- The pull-out model was in good agreement with experimental values, obtaining for the force corresponding to the instant when the steel sheet started to slip a value of 80% of the experimental value, even with the unknown value for the coefficient of Coulomb.
- The experimental program divided in two groups the experimental tests according to their mechanism of failure, by changing the span loaded and the area of contact used.
- For the experimental tests conditioned by punching shear was possible to identify a brittle behavior until rupture and for the experimental tests conditioned by longitudinal shear a ductile behavior.
- The composite slab model predicted quite well the ultimate load, comparing to experimental test with the load positioned in the middle span (nº 1, 2, 3 and 7), reaching 90% and 87% of the experimental value.
- On the other hand, the simplified model of the composite slab achieved low values of the experimental load, mainly for the yield tension obtained from the pull-out experiment.
- The prediction of the failure load, in the case of experimental tests conditioned by punching shear was nearly the real value, precisely 99%, and in cases of experimental

tests governed by longitudinal shear the failure load calculated according to m-k method and partial connection methods differed 8 kN and both were too conservative.

- The new simplified method proposed by Crisinel when compared to the reduced moment obtained by the partial connection method was too conservative.

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