Steel and Composite Structures, Vol. 8, No. 5 (2008) 361-388 361
DOI: http://dx.doi.org/10.12989/scs.2008.8.5.361

Experimental and analytical behaviour of composite slabs

Emanuel Lopes

Civil Engineering Department, Polytechnic Institute of Castelo Branco, Castelo Branco, Portugal

Rui Simões*

ISISE, Civil Engineering Department, University of Coimbra, Coimbra, Portugal

(Received March 21, 2007, Accepted May 21, 2008)

Abstract. The Eurocode 4 presents some negative aspects in the design of composite slabs by the *m-k* Method or the Partial Connection Method. On one hand, the component chemical adherence is not accounted for in the connection between the profiled steel sheet and the concrete. On the other hand, the application of these methods requires some fitting parameters that must be determined by full scale tests. In this paper, the Eurocode 4 methods are compared with a method developed at the Federal Polytechnic School of Lausanne, based on pull-out tests, which can be a valid alternative. Hence, in order to calculate the necessary parameters for the three methods, several tests have been performed such as the full scale test described in Eurocode 4 and pull-out tests. This last type of tests is of small dimensions and implicates lower costs. Finally, a full-scale test of a steel-concrete composite slab with a generic loading is presented, with the goal of verifying the analytical formulation.

Keywords: composite slabs; curvature; longitudinal shear; shear span; slip phenomenon; moment-curvature relation; pull-out test; full-scale test; small-scale test.

1. Introduction

A composite slab is a structural element composed by a cold formed steel sheet in connection with concrete (Fig. 1). The profiled sheeting can have several functions, among others: *i*) offer an immediate working platform; ii) acts as a stay-in-place formwork and iii) acts as slab reinforcement.

There are two different phases to consider in design: i) Formwork-profiled sheeting as shuttering and working platform and ii) Composite slab-after the concrete hardening the steel sheet combines structurally with concrete.

A composite slab may collapse in three different ways: vertical shear, longitudinal shear or bending (usually steel sheet yielding). For building spans between 2 and 4.5 m, the main failure mode is the longitudinal shear.

Besides the brief description of the methods predicted in the European rules (EN 1994-1-1 2007) for the evaluation of the longitudinal shear resistance of composite slabs, it is the objective of this paper: *i*) to describe the experimental tests carried out to obtain results to calibrate the semi-empirical parameters for the application of previous methods; ii) to apply and calibrate a new model (developed by Crisinel and Carvajal 2002), designated in this paper by the New Simplified Method and iii) to evaluate the

*Corresponding author, E-mail: rads@dec.uc.pt

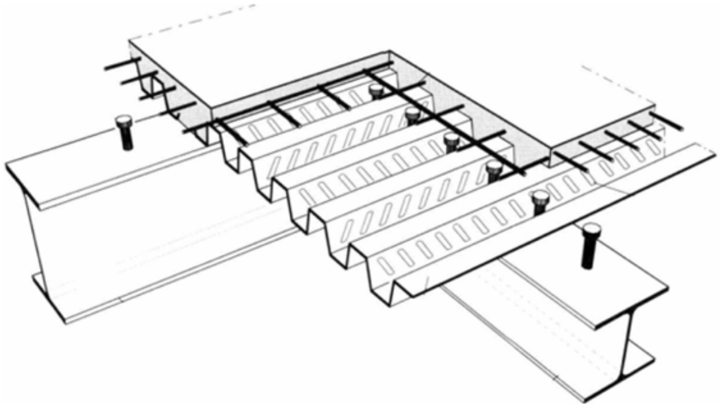


Fig. 1 Composite steel-concrete slab

accuracy of the two type of methods, when compared with experimental results.

2. Longitudinal shear resistance in composite slabs

2.1. Methods predicted in the EN 1994-1-1

The longitudinal shear verification foreseen in EN 1994-1-1 relies on the *m-k* Method (Porter and Ekberg 1976). According to this method, the determination of *m* and *k* parameters is achieved through a numerical analysis of the data measured from composite slab full-scale tests (Fig. 2). In this method the design shear resistance ($V_{l,Rd} = V_t$) is given by Eq. (1):

$$\frac{V_t}{bd_p} = m\left(\frac{A_p}{bL_s}\right) + k \tag{1}$$

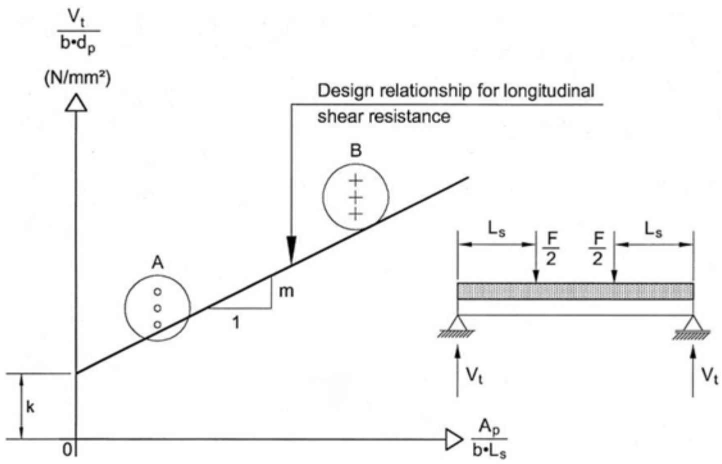


Fig. 2 *m-k* Method

where: V_t is the support reaction measured during the test; b is the width of the slab; d_p is the depth of the centroidal axis of the profiled sheet measured from the slab top; A_p is the cross sectional area of the profiled sheet and Ls is the shear span.

Although the *m-k* Method presents simple design equations, it has some disadvantages: i) It's a semi-empirical method with small physical meaning; ii) it does not exploit the longitudinal shear resistance guaranteed by end anchorage or by bearing friction and iii) the method requires the execution of a minimum of six composite slabs full-scale tests.

EN 1994-1-1 presents an additional method to verify the sagging moment resistance of ductile slabs in partial connection: the Partial Connection Method (Bode 1990). This method is similar to the one used in composite beams design. When compared to *m-k* Method, it is possible to point out some advantages: it presents a physical basis and it's also more intuitive. The method has its basis on a graphic that relates the bending moment with the shear connection degree (Fig. 3). The longitudinal shear strength τ_u is determined from a full-scale tests series, through the Eq. (2):

$$\tau_u = \frac{\eta N_{cf}}{b(L_s + L_o)} \tag{2}$$

or if friction is considered, through the Eq. (3):

$$\tau_u = \frac{\eta N_{cf} - \mu V_t}{b(L_s + L_o)} \tag{3}$$

where: η represents the shear connection degree of the tested slab; N_{cf} represents the compressive normal force applied in concrete with full shear connection; L_o is the cantilever length of the slab near the support and μ is the friction coefficient. The remaining symbols have the already mentioned meanings.

The Partial Connection Method guarantees more economical designs because it takes advantage of

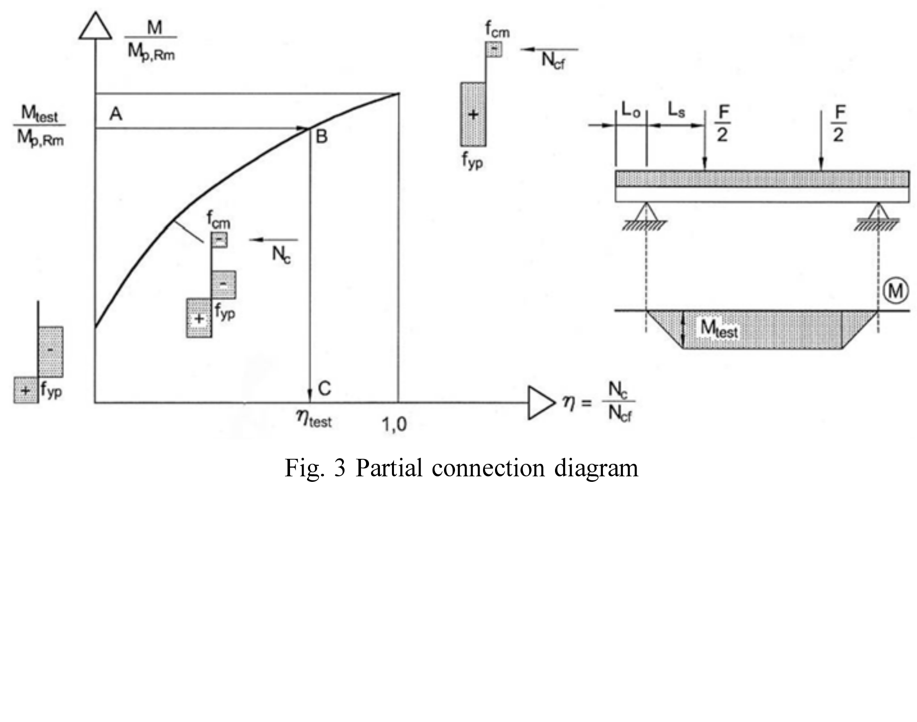


Fig. 3 Partial connection diagram

the profiled sheets ductile behaviour with good mechanical interlock and large spans. However, there are some disadvantages to mention: *i*) The method is only applicable to ductile slabs; *ii*) it requires full-scale tests in composite slabs and *iii*) it is impossible to extrapolate test results for slabs with a smaller span and if the same is done for composite slabs with a larger span the procedure will be too secure.

2.2. The New Simplified Method

Recently, in the Federal Polytechnic School of Lausanne, in order to verify composite slabs behaviour in partial connection, a new method was developed - The New Simplified Method (Crisinel and Carvajal 2002). This method does not rely on full-scale tests or on numerical simulation and can be applied to all types of composite slabs, fragile or ductile, and to all types of profiled sheeting.

This method is based on the determination of the moment-curvature relation of all composite slabs critical sections. The moment-curvature relation immediately allows knowing the slabs maximum resistant moment in partial connection. The deflection of the slab can be determined through the integration of the critical sections curvature.

The steel sheeting-to-concrete connection properties are determined from small-scale pull-out tests, similar to the ones Daniels and Crisinel accomplished (Daniels and Crisinel 1988). The longitudinal shear strength is guaranteed by chemical bond (τ_{slip}) and mechanical interlock ($\tau_{\max}$).

Figs. 4 and 5 represent the results (stress-displacement relation) of Pull-Out Tests of composite slabs with fragile and ductile behaviour, respectively. They also represent the adopted behaviour for the analytical model (interrupted line) in both cases.

The analytical model takes into account the physical components of the steel-concrete connection, which are chemical bond and mechanical interlock (from the pull-out tests results), friction near support and end anchorage.

The physical model which represents the slab in this method is similar to the one that represents a composite beam. The profiled sheeting is modelled as an I section with the same area and inertia of the original sheeting section. The same procedure is used in concrete, though it is modelled as a rectangular section. The real section transformation of the composite slab into the modelled section is represented in Figs. 6 and 7.

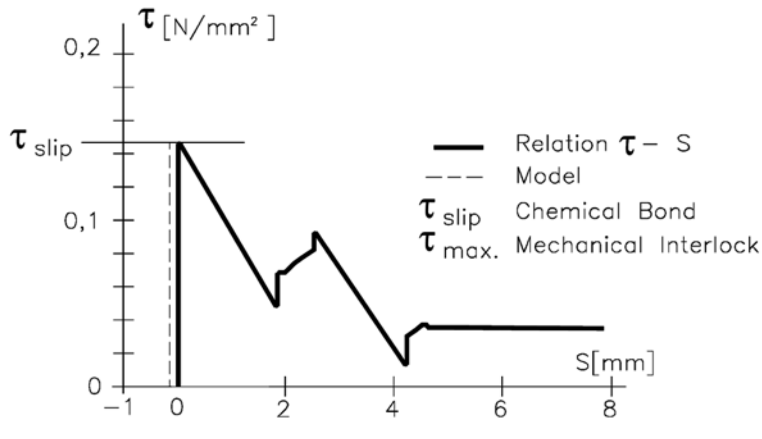


Fig. 4 Stress- displacement relation of a Pull-Out Test of a composite slab with fragile behaviour

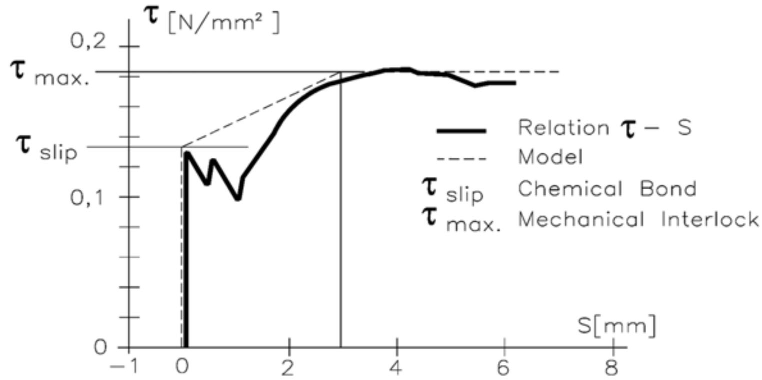


Fig. 5 Stress- displacement relation of a Pull-Out Test of a composite slab with ductile behaviour

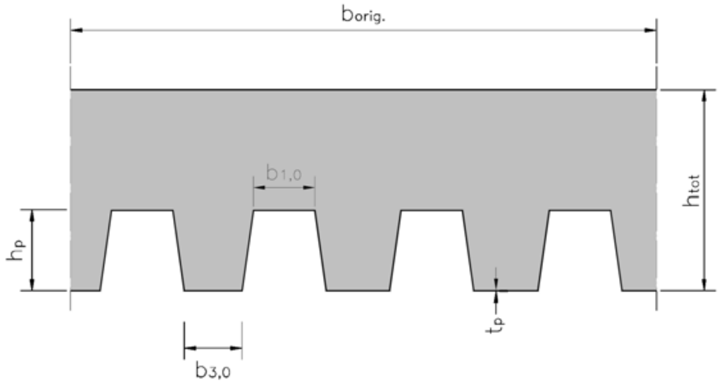


Fig. 6 Real section of the composite slab

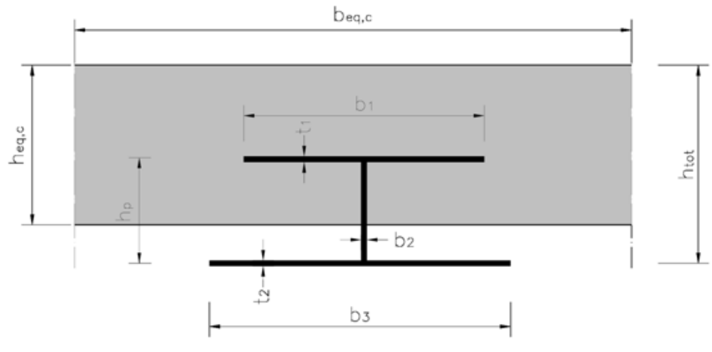


Fig. 7 Modelled section

As referred, the New Simplified Method is based on the determination of a tri-linear moment-curvature relation at the critical section of the composite slab (Fig. 8).

The line segments represented on the diagram are associated to each phase of the composite slab behaviour, in particular:

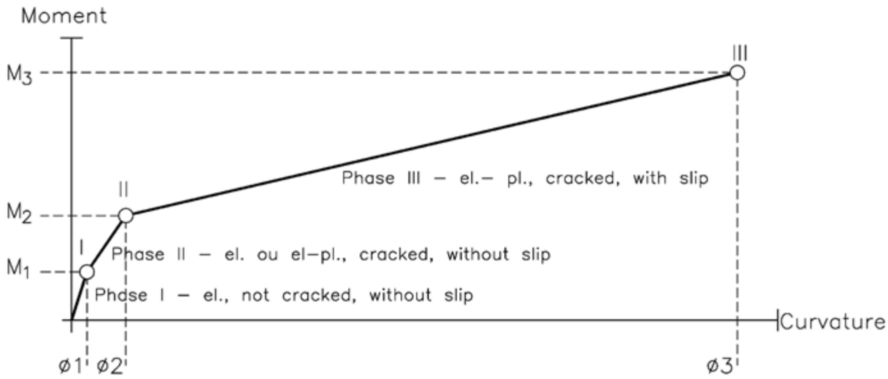


Fig. 8 Tri-linear moment-curvature

Phase I. Linear elastic behaviour - Total interaction between steel and concrete and no concrete cracking.

This phase has the following assumptations: a) linear elastic behaviour; b) concrete not cracked; c) total interaction between steel and concrete; d) steel extension equal to concrete extension and e) the equivalent steel section of the concrete determined by the relation between the modules of elasticity of steel and concrete.

The first phase of the moment-curvature relation ends after the first crack in concrete. Point I is determined.

Phase II. Elastic or elasto-plastic behaviour - Concrete cracking and total interaction between steel and concrete.

After Point I of the moment-curvature relation, the critical section in study is cracked. The moment-curvature relation is now with a cracked elastic or elasto-plastic behaviour. The assumptions of this phase are:

a) if the steel and concrete stresses are below yield and characteristic stresses, respectively, the section is in elastic behaviour; if not, it is in elasto-plastic behaviour;
b) cracked concrete;
c) total interaction between steel and concrete; this indicates that the longitudinal stress is inferior to τ_{slip};
d) steel extension equal to concrete extension.

The second phase ends when the first slip occurs. The longitudinal stress equals τ_{slip} and Point II is defined.

Phase III. Non-linear elasto-plastic behaviour - Concrete cracking and partial connection between steel and concrete.

When Point II of the moment-curvature relation is reached, the slip between steel and concrete becomes effective. In that moment the third phase of the moment-curvature relation begins. This phase only happens with ductile slabs.

Normally, Point III of the moment-curvature relation represents the complete rupture of the composite connection (infinite slip between steel and concrete).

The assumptions of this phase are:

a) cracked concrete and effective slip between steel and concrete;
b) the rupture of the connection (or of one of their components) implicates the rupture of the

composite slab;

c) after slip, concrete and steel have the same curvature.

For non-ductile composite slabs the second point represents the point of collapse, which means that the maximum moment has been attained. For slabs with ductile behaviour, the third point indicates that maximum mechanical longitudinal shear stress has been attained, which represents the rupture of the slab (infinite slip).

In this method it is possible to consider the effect of supplementary parameters, such as friction and end anchorage.

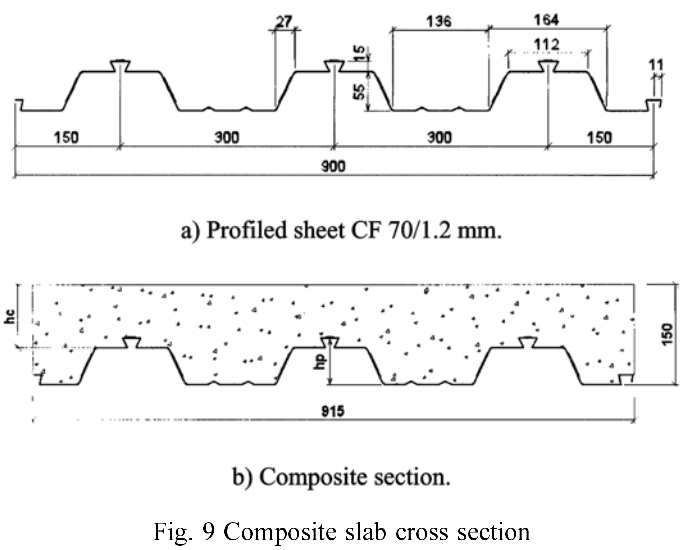
3. Experimental tests for calibration of longitudinal shear methodologies

3.1. Test results and parameters calculation according to EN 1994-1-1

3.1.1. Test results

It will be presented a test programme in order to determine m, k and τ_u parameters, that concerns to ComFlor 70 (CF70/ 1.2) profiled sheeting from Corus, with a nominal thickness of 1.20 mm (Fig. 9a). Six composite slab models were tested, with an overall thickness h_t of 150 mm. Models 1, 2 and 3 had a 2,200 mm length and the remaining ones had 3,500 mm length. All models had a 915 mm width and exhibited a cross section similar to the one represented in Fig. 9-b. Crack inducers were placed on the models at the quarters spans (L/4 and 3L/4-Fig. 10). The crack inducers provide a better definition of the shear span L_s and allow the elimination of concrete resistance in tension (Lopes 2005).

As Fig. 10 shows, the composite slabs were tested simply supported. Two line loads were applied at the quarter spans, according to the procedure schematized in Fig. 11; initially, the slab models were subjected to a cyclic load (initial test) and after, the load was increased statically until rupture (subsequent test). The first slab of the three tested models of each group was only subjected to the static test (subsequent test), in order to determine the cyclic load levels for the other two.



a) Profiled sheet CF 70/1.2 mm.

b) Composite section.

Fig. 9 Composite slab cross section

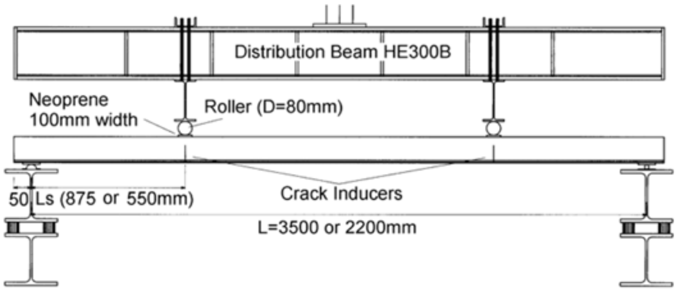


Fig. 10 Full-scale test set-up

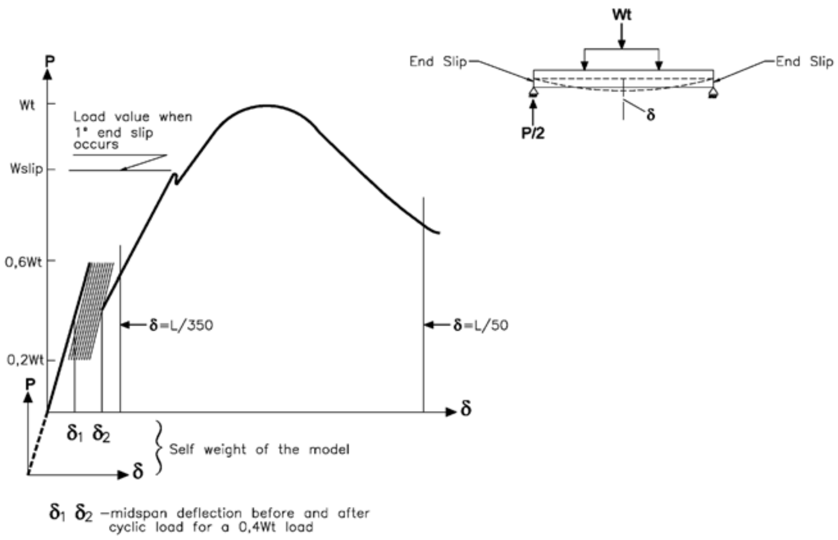


Fig. 11 Full-scale test procedure

The initial test lasted at least three hours and was composed by 5000 cycles. It was controlled by strength and the upper and lower load limits applied were, respectively, 0.6 W_t and 0.2 W_t. The subsequent test was controlled by displacement until rupture and lasted at least one hour.

The tests main goal is to determine V_t and M_{test} (maximum moment applied on the test) in order to calculate m, k and τ_u. It is also important to measure the end slip, because it allows the determination of the behaviour of the steel-concrete connection (ductile or non-ductile). With this purpose, the models were instrumented (Figs. 12 and 13) and the variables indicated in the Table 1 were measured.

Tension tests (according to EN 10 002-1) were performed in specimens obtained from the flanges and webs of profiled sheets, in order to determine the real properties of the steel. From these tests the average values of yield stress, ultimate stress and elasticity modulus were attained. Four cylindrical specimens ($\varnothing 150 \times 300$ mm) were made for each slab, with the purpose to investigate the concrete compressive strength.

The full-scale tests results are represented through load/displacement curves, particularly the following: i) load/midspan deflection curve; ii) load/end slip curve and iii) load/stress in profiled sheet curve (Lopes 2005).

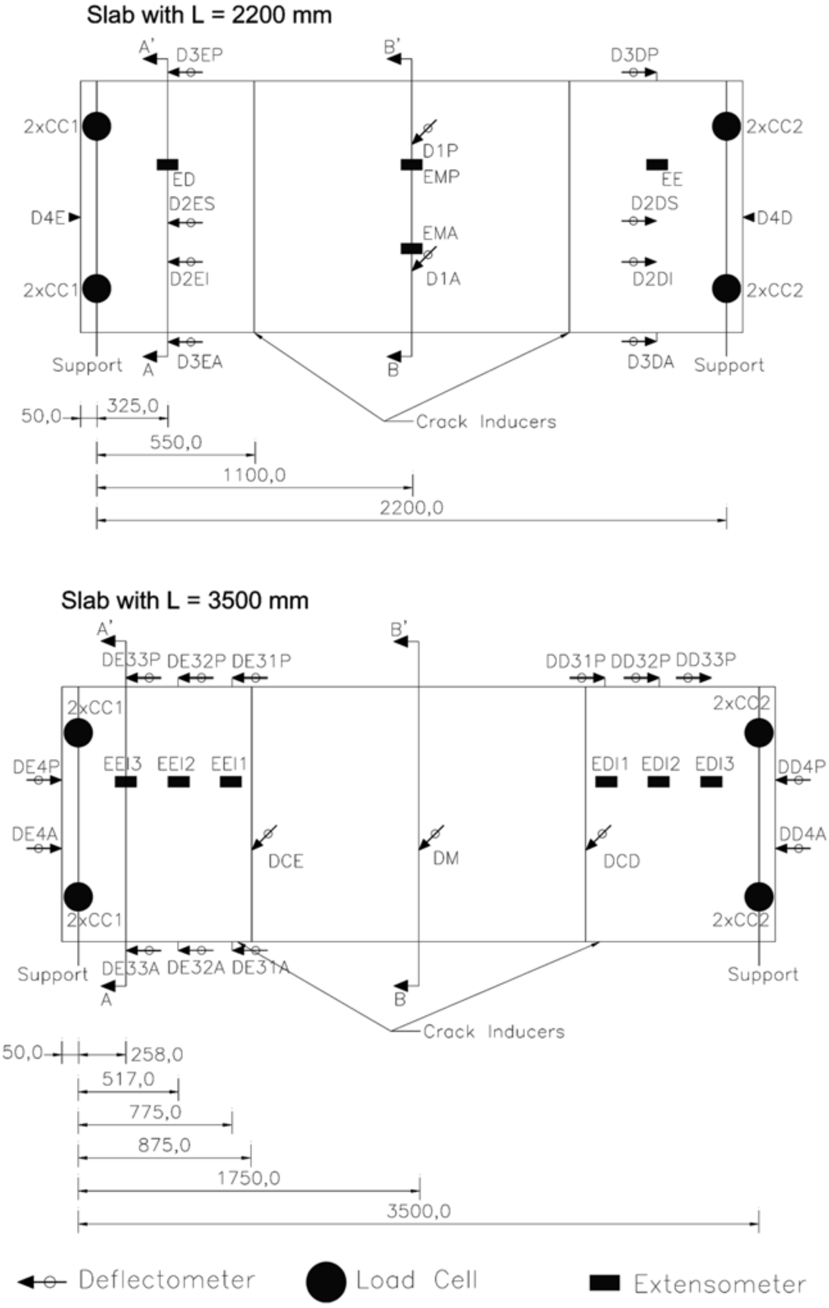


Fig. 12 Instrumentation of the slabs with $L = 2200$ mm and $L = 3500$ mm

Tables 2 and 3 present load or displacement values which represent slab behavioural changes, such as: the maximum load applied to the slab (W_t); the first crack load (W_{1crack}); the first and second end slip load (W_{1slip}, W_{2slip}); the load in which end slip is equal to 0.1 mm ($W_{0.1\ mm}$); the cyclic load limits ($0.2W_t$ $-0.6W_t$); the load for a midspan deflection of L/350 (W_L/350); the midspan deflection for maximum

Fig. 13 Instrumentation details of the slabs with L = 3500 mm

Table 1 Tests instrumentation

Measurements	Slabs 1, 2, 3	Slabs 4, 5, 6
Mid-span deflection	2 displacement transducers	1 displacement transducer
Applied load	4 load cell by support	4 load cell by support
End slip	1 displacement transducer at the extremity of the slab	2 displacement transducers at the extremity of the slab
Slip along the shear span	4 displacement transducers per side	6 displacement transducers per side
Stress variation in the profiled sheet when chemical bond rupture occurs	1 extensometer	3 extensometers
Stress at the midsection of the profiled sheet	2 extensometers	-

Table 2 Significant load values

Slab model	W_t (kN)	W_{1crack} (kN)	W_{1slip} (kN)	W_{2slip} (kN)	$W_{0.1mm}$ (kN)	$0.2W_t$ - $0.6W_t$ (kN)	*Effective cyclic load* (kN)	$W_{L/350}$ (kN)
1	106.69	39.24	55.62	57.05	59.58	-	-	53.99
2	107.75	41.20	55.73	55.85	54.22	21.55/64.65	14.72/68.67	56.86
3	101.84	42.77	49.83	49.83	51.17	20.37/61.10	14.72/68.67	56.48
4	81.84	22.20	41.80	46.89	46.93	-	-	39.48
5	90.70	26.71	47.61	48.23	48.23	18.14/54.42	16.19/56.43	40.85
6	94.01	23.54	46.29	46.09	45.22	18.80/56.41	16.19/56.43	42.08

applied load (δ_{Wt}); the midspan deflection at the end of the test (δ_{max}); the midspan deflection when first crack and the first and second end slip occur (δ_{1crack}, δ_{1slip}, δ_{2slip}) and the end slip for maximum applied load ($Slip_{Fmax}$). Fig. 14 shows the load decrease in the slab 2 when the first and second end slip occurred. From the tests analysis it is important to mention that the maximum load applied to the slab is

Table 3. Significant displacements values

Slab model	$\delta_{w/t}$ (mm)	δ_{1crack} (mm)	δ_{1slip} (mm)	δ_{2slip} (mm)	$Slip_{Fmax}$ (mm)	δ_{max} (mm)
1	24.84	4.16	6.76	8.66	2.33	44.58
2	19.84	2.72	4.08	5.20	2.03	44.72
3	18.50	3.14	4.22	4.22	1.76	39.54
4	40.92	3.74	11.11	14.60	1.93	70.01
5	46.10	4.04	14.90	14.90	1.76	74.50
6	45.68	3.42	12.04	13.18	1.83	70.40

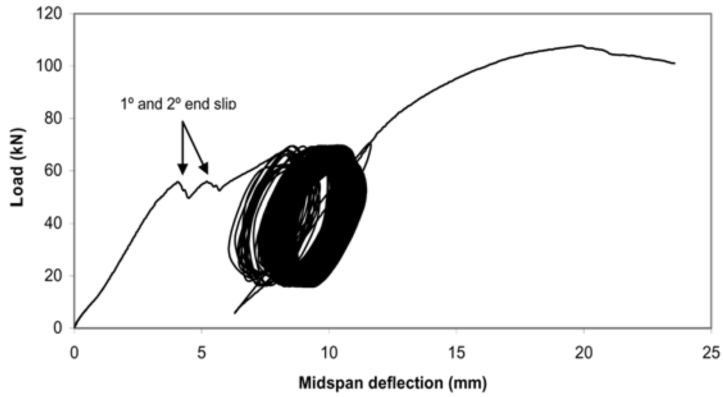


Fig. 14 Load-mid-span deflection curve of slab model 2

almost twice the load that causes total detachment of the concrete (which occurs when $W = W_{2slip}$).

The detachment between steel sheeting and concrete occurs from the section where the load is applied until the support, which implies that when end slip takes place there are sections closer to the load application zones that already present a significant slip.

The load/midspan curves of both slabs groups ($L = 2200$ mm and $L = 3500$ mm), including the average stiffness on-going, are shown in Figs. 15 and 16.

3.1.2. m and k parameters

Table 4 indicates the sum of all applied loads, including the self weight (W_t) and the reaction in the slab supports (V_t).

Eq. (4) and Eq. (5), respectively, define the abscise and the ordinate of the points that belong to groups A and B.

$$x = A_p/(bL_s) \tag{4}$$

$$y = V_{tk}/(bd_p) \tag{5}$$

The *m* and *k* values are, respectively, the slope and the origin ordinate of the line defined by the characteristic points of groups A and B, described in Fig. 17.

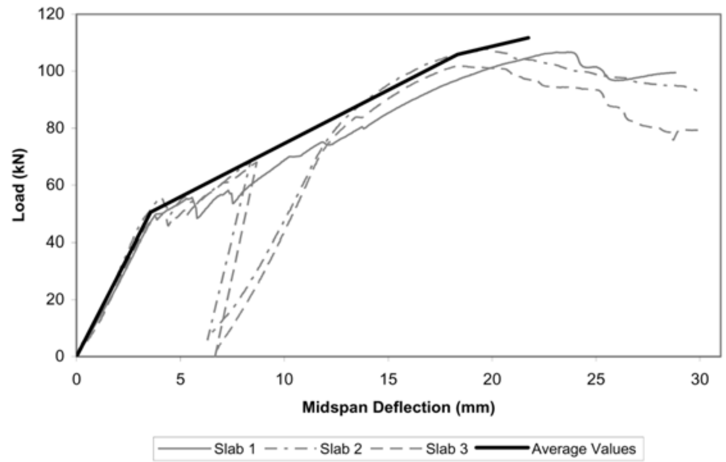


Fig. 15 Load vs. midspan deflection of slabs 1, 2 and 3 (without the cycles)

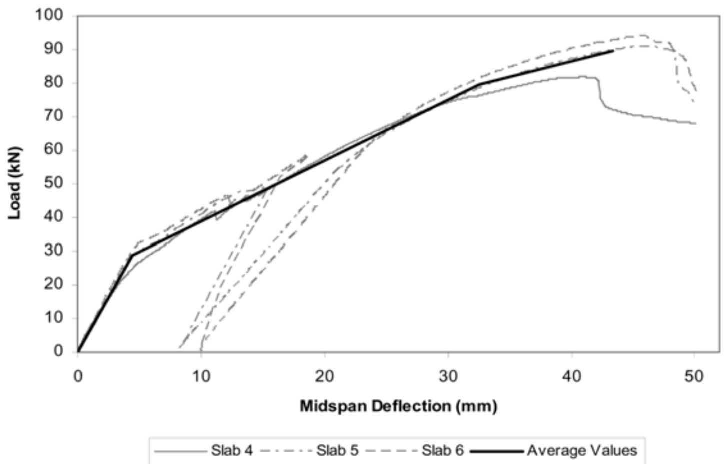


Fig. 16 Load vs. midspan deflection of slabs 4, 5 and 6 (without the cycles)

Table 4 Summary of the composite slabs design and applied loads

Slab model	L (mm)	*Self weight* (N)	W_t (N)	V_t (N)
1	2200	6414	113104	56552
2	2200	6414	114164	57082
3	2200	6463	108303	54151
4	3500	10039	91879	45940
5	3500	10116	100816	50408
6	3500	10116	104126	52063

3.1.3. $\tau_{u,Rd}$ parameter

Slabs ductility was determined from the results of slab model 1. This model presents a ductile behaviour because the maximum load (W_t) exceeds the load causing an end slip of 0.1 mm by more

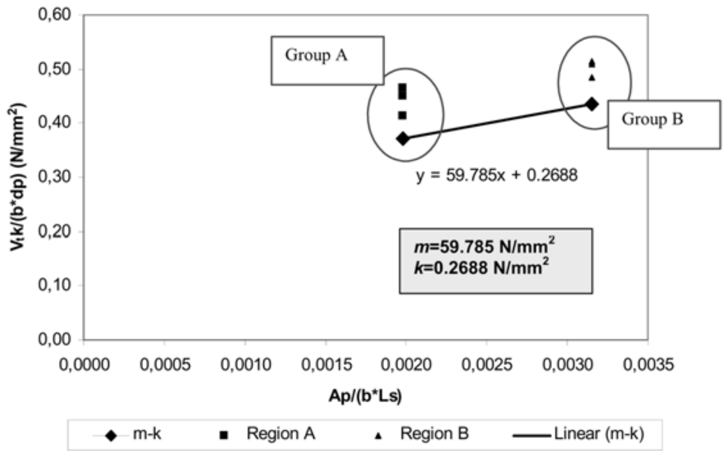


Fig. 17 Determination of the m and k parameters of the composite slab

than 10% (Wt > 1.1 $W_{0.1\,mm}$). $\tau_{u,Rd}$ has been determined from slab models 4, 5 and 6.

The slab has a sagging moment resistance of $M_{p,Rm}$ in total connection. However, the effectively maximum applied moment during the test, M_{test}, can be determined through the product of V_t, by the shear length L_s. Those values are indicated in the Table 5, as well as $M_{test} / M_{p,Rm}$ relation value. From the partial connection diagram of the slab (Fig. 18) it is possible to calculate the shear connection degree (η) and the longitudinal shear strength (τ_u) for each test (Table 6). Characteristic longitudinal shear strength ($\tau_{u,Rk}$) is calculated after a statistic model application (defined in the Annex D of EN 1990) to the values of each slab longitudinal shear strength (τ_u). Table 7 represents the characteristic ($\tau_{u,Rk}$) and the design ($\tau_{u,Rd}$) values of the longitudinal shear strength, with and without friction.

Table 5 Moment applied during the test

Slab model	M_{test} (kNm)	M_{test} / b (kNm/m)	$M_{test} / M_{p.Rm}$
4	40.197	44.124	0.6460
5	44.107	48.416	0.7089
6	45.555	50.006	0.7321

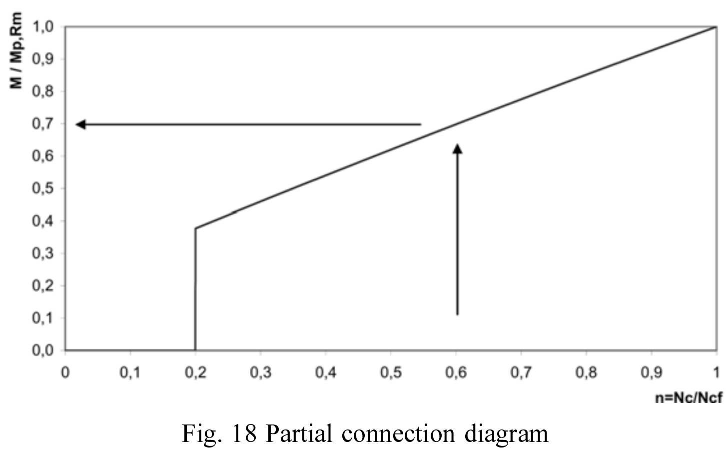


Fig. 18 Partial connection diagram

Table 6 Shear connection of the slab models 4, 5 and 6

Slab model	$M_{test}/M_{p.Rm}$	$\eta = \frac{N_c}{N_{cf}}$	$\tau_u = \frac{\eta N_{cf}}{b(L_s+L_0)}$ [kN/m^2]	$\tau_u = \frac{\eta N_{cf} - \mu V_t}{b(L_s+L_0)}$ [kN/m^2]
4	0.6460	0.5335	348.32	323.49
5	0.7089	0.6140	400.88	373.63
6	0.7321	0.6440	420.47	392.33

Table 7 Design and characteristic shear connection value

	$\tau_{u,Rk}$ [kN/m^2]	$\tau_{u,Rd} = \frac{\tau_{u,Rk}}{\gamma_{vs}}$ [kN/m^2]
Without friction	319.38	255.50
With friction	295.87	236.70

3.2. Test results and parameters calculation according to the New Simplified Method

The tests to determine τ_{slip} and τ_{max} parameters will now be presented. These tests concern to ComFlor 70 profiled sheeting (with a nominal thickness of 1.20 mm). The function of those parameters is to quantify the connection between steel sheet and concrete, in order to apply the New Simplified Method (Crisinel and Carvajal 2002).

The specimens are composed by two ribs of the profiled sheeting (placed in opposite ways), intercalated by two steel sheets (5 mm thickness). Two concrete blocks are attached on the two opposite sides of the profiled sheets. The tension force (applied on top of the profiled sheets) is transferred to the specimens' base by four bar ∅12 with a 495 mm length, anchored in concrete. The specimens have the dimensions and shape indicated in Fig. 19. The connection between profiled sheets and steel sheets with a 5 mm thickness, as well as the connection between profiled sheets is made by bolting. Fig. 19 shows also the specimens immediately after concrete cover (Lopes 2005).

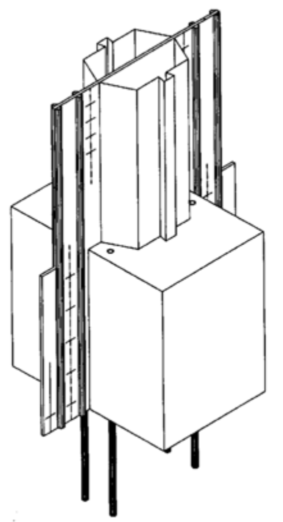
Figs. 20 and 21 display the test scheme, as well as its components. According to Daniels and Crisinel 1988, a pair of horizontal forces, with a total intensity of 0.16 kN, should be applied to specimens. The goal is to simulate the self weight of the concrete acting as a vertical load on the profiled sheet of the slab. The measured values were: the tension force (F_{tot}), the horizontal forces applied (H_1, H_2) and the relative slip between profiled sheets and the concrete blocks (C_1, C_2). The effective instrumentation is represented in Fig. 22.

By analysing Table 8, it is possible to compare maximum shear resistance before first slip (F_{slip}) and in failure (F_{max}).

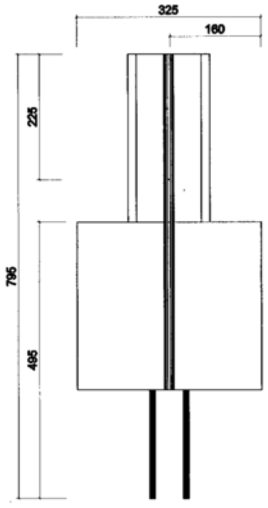
Longitudinal shear strength before the first slip (τ_{slip}) and for maximum force (τ_{max}), are determined through the Eqs. (6):

$$\tau_{slip} = \frac{F_{slip}}{2l_b b_s}; \qquad \tau_{max} = \frac{F_{\max}}{2l_b b_s} \tag{6}$$

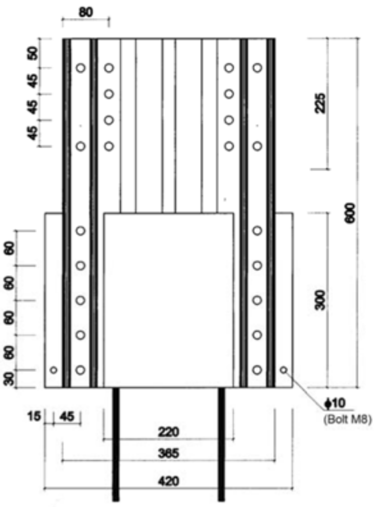
where b_s represents the distance between the centres of profiled sheeting ribs and l_b the concrete blocks height. The obtained values are: $\tau_{slip} = 183.5$ kPa and $\tau_{max} = 295.7$ kPa.



a. Shape.



b. Lateral view.



c. Frontal view.

d. Specimen after concrete cover.

Fig. 19 Pull-out test specimen

4. Application of the new simplified method to the tested slabs

For the application of the New Simplified Method, three tests were performed in slabs with 3500 mm spans. The real values of slabs dimensions (average values) are described in the Table 9. The values of the Table 10 describe the steel-concrete connection resistance. The yield strength of the steel sheet (f_{yp}), the ultimate strength and the young modulus of the concrete (f_{cm}, E_{cm}) are the following: f_{yp} = 382.72 MPa; f_{cm} = 31.54 MPa; E_{cm} = 31.05 GPa. The slabs were submitted to the average forces indicated in the Table 11.

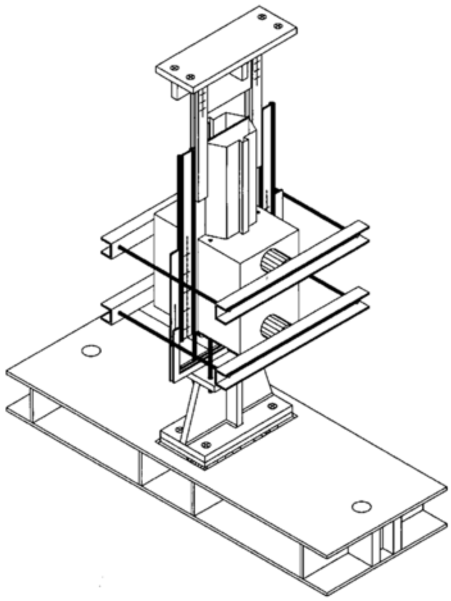


Fig. 20 Pull-out test set-up

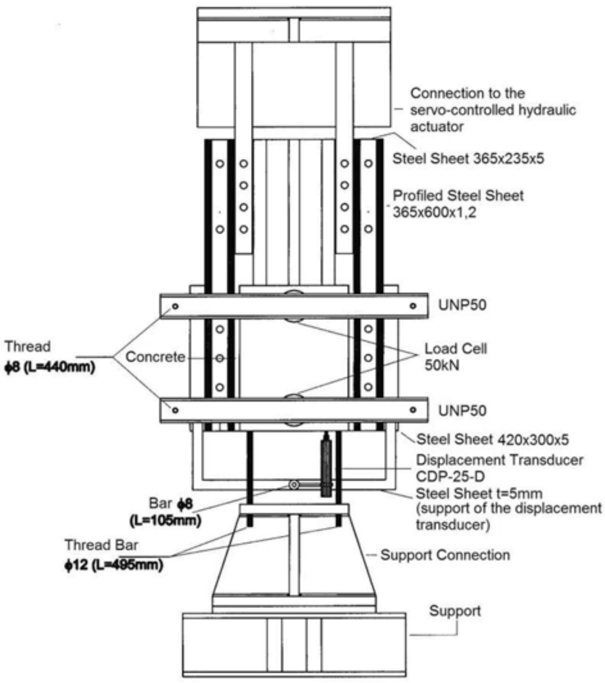


Fig. 21 Pull-out test components

In the analysis of the mentioned slabs group by the New Simplified Method, it is necessary to use the connection resistances determined by pull-out tests; they are the following:

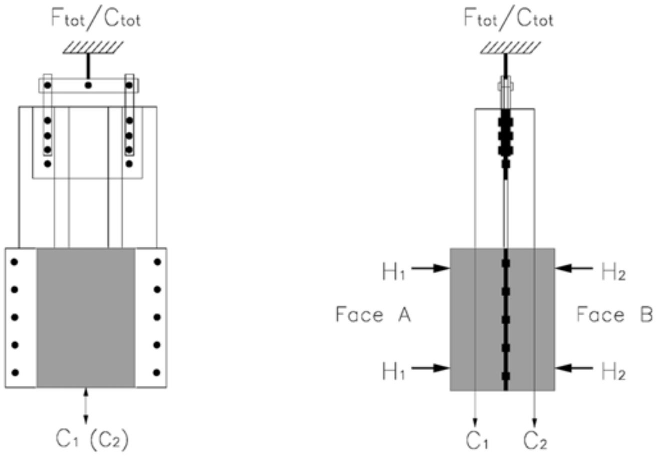


Fig. 22 Instrumentation and measurements of the tests

Table 8 Fslip and Fmax values increased by the specimens own weight

Specimen	SW_{spec} [kN]	$Fslip + SW_{spec}$ [kN]	$F_{max} + SW_{spec}$ [kN]
1	0.567	-	55.996
2	0.569	27.470	49.951
3	0.570	39.045	54.607
Average value		33.257	53.518

Table 9 Real values of slabs dimensions

Width – $\boldsymbol{b}$ (mm)	900
Slab thickness – $\boldsymbol{h}$ (mm)	152.67
Level of elastic neutral axis – $\boldsymbol{e}$ (mm)	30.32
Level of plastic neutral axis – $\boldsymbol{e_p}$ (mm)	33.00
Steel sheet section – $\boldsymbol{A_p}$ (mm^2/m)	1578.00
Plastic moment of steel sheet – $\boldsymbol{M_{pla}}$ (kNm/m)	11.48

Table 10 Steel-concrete connection resistance

Shear length – $\boldsymbol{L_s}$ (mm)	875
$\boldsymbol{m}$ parameter (MPa)	56.198
$\boldsymbol{k}$ parameter (MPa)	0.347
τ_u (kPa)	389.89
$\tau_u^{friction}$ (kPa)	363.15
μ	0.50
$\boldsymbol{V_t}$ (kN)	49.47

τ_{slip} = 183.54 kPa and τ_{max} = 295.68 kPa. Fig. 23 presents the application of the New Simplified Method for the slabs group here analysed (L = 3500 mm). With this method it is possible to obtain the moment-curvature relation for the critical section (maximum sagging moment section).

Table 11 Maximum internal forces developed on the tested slabs

Slab span [mm]	Total applied load (W_t) [kN]	Self weight [kN/m]	Maximum transverse shear (V_t) [kN]	Maximum sagging moment M_{test} [kNm]
3500	88.85	2.80	49.47	43.41

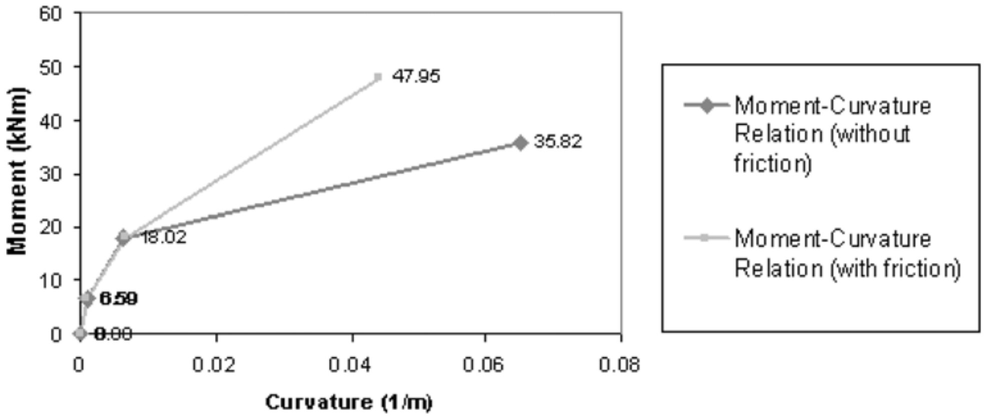


Fig. 23 Moment-curvature relation for the composite slabs of 3500 mm

In the application of the New Simplified Method, two curves were determined: one curve in which the additional resistance due friction (with the value of 0.5 proposed in EN1994-1-1) is considered and another where that resistance is ignored.

From the analysis of the graphic in Fig. 23 it is possible to observe that friction consideration rises the resistant moment for Points II and III, and reduces Point III curvature.

The test structural scheme is represented in Fig. 24. Assuming that there is a linear variation of the curvature between the support and the section where the load is applied (New Simplified Method critical section) it is possible (by curvature integration) to determine the slab midspan deflection, without needing to know the stress level in the section (elastic, elasto-plastic, ...).

The midspan deflection is given by Eq. (7):

$$\delta_{midspan} = \int_L (\phi(x)\overline{M})dx = \frac{11}{96}\phi \cdot L^2 \tag{7}$$

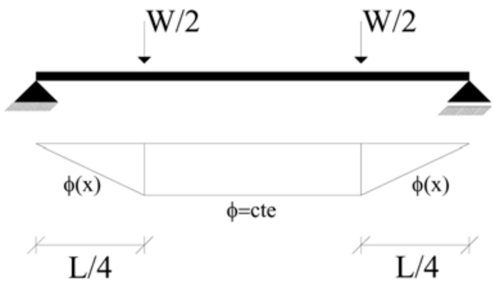


Fig. 24 Structural scheme for the EN 1994-1-1 composite slabs full scale tests

where $\overline{M}$ represents the virtual moment due to a vertical linear load applied at midspan.

For the slabs group in study, Table 12 indicates the moments, the curvature and the midspan deflection for the three points of the moment-curvature relation.

For the same structural scheme (Fig. 24) it is possible to obtain, from the maximum moment, the total load W applied to the slab.

By comparing the midspan load-deflection relation (disregarding slabs self weight) subjected to two symmetrical loads, with the results obtained from the New Simplified Method, it was possible to attain the graphic in Fig. 25. Additionally, the approximated behaviour of the slabs was introduced in the same graphic (Lopes and Simões 2006).

Through the analysis of the curves presented in Fig. 25 it is possible to observe that the maximum moment foreseen by the New Simplified Method approaches the maximum moment applied to the slabs if the resistance by friction is not considered. In this case the maximum resistant moment is practically identical to the minor maximum moment applied in the slabs group. If the friction additional resistance is taken into account the method provides unsafe resistant moments.

In relation to stiffness, the method simulates accurately the composite slabs behaviour (when subjected to two symmetrical linear loads), as long as the additional resistance guaranteed by friction is

Table 12 Maximum moment, critical section curvature and midspan deflection for the groups of slabs with a 3500 mm span, determined by the New Simplified Method

Span [mm]	Friction is taken in consideration?	Moment-curvature relation points	M_{max} [kNm]	Curvature ϕ [1/m]	W [kN]	$\delta_{midspan}$ [mm]
		Point I	6.59	0.000922	15.06	1.29
3500	No	Point II	17.54	0.006343	40.09	8.90
		Point III	35.82	0.064896	81.87	91.09
		Point I	6.59	0.000922	15.06	1.29
3500	Yes	Point II	18.02	0.006519	41.19	9.15
		Point III	47.95	0.044211	109.6	62.06

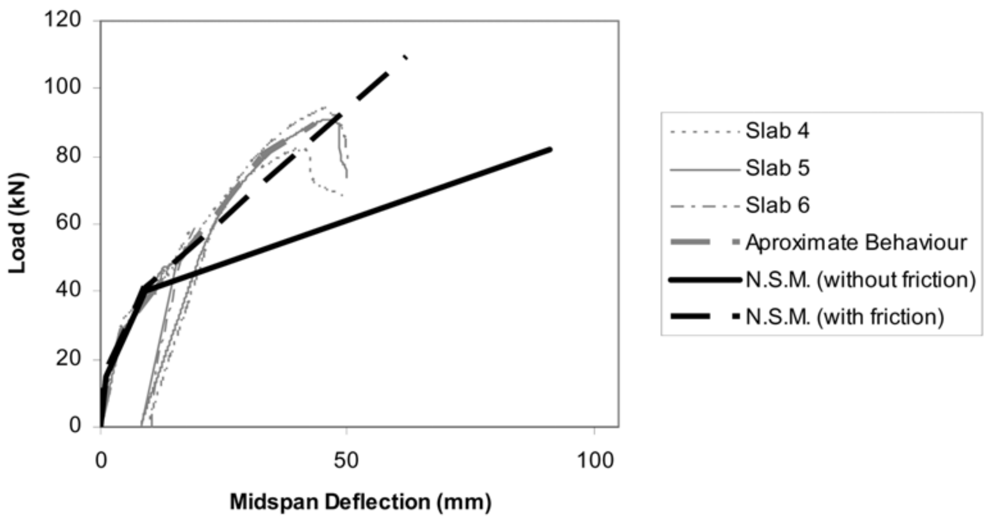


Fig. 25 Load vs. midspan deflection of the group of slabs with $L = 3500$ mm

taken into consideration. Until Point II, the friction has small influence on the method; however, from this point and as long as the rupture occurs by longitudinal shear, this implies a smaller curvature needed to attain the maximum resistant moment (in partial connection). This is the main reason for the big difference between the midspan deflections foreseen by the method when friction is considered and when it is not.

5. Full scale test of a steel-concrete composite slab in real conditions

5.1 Test procedure

The program of experimental tests accomplished culminated with the execution of a composite slab test, with the dimensions b = 900 mm, L = 4000 mm and h = 201 mm (measured values). The test load was a distributed load and a midspan line load.

The final test goals were:

- To determine the composite slab deflection at serviceability limit states (*SLS*).
- To verify the slab resistance at ultimate limit states (*ULS*).
- To determine the slab effective resistance and to verify the slab resistance reserve concerning to the ultimate limit states.
- To analyse the slab through the methods indicated in EN 1994-1-1 and by the *New Simplified Method*, comparing the obtained results with the ones that were experimentally measured.

The distributed load was applied by concrete cubic and parallelepiped specimens that existed in the laboratory where the tests took place (Laboratory of test materials and structures of Civil Engineering Department of University of Coimbra - Portugal). The line load was applied by a hydraulic jack, through an 80 mm steel roller with the width of the slab.

The slab was designed to the ultimate limit states - according to the fundamental combination - and verified to the serviceability limit states - through the frequent combination. Table 13 presents the predicted loads according to the combinations referred.

The composite slab was instrumented with the goal of measuring the following values:

- The end slip -2 displacement transducers with 50 mm of capacity in each end;
- The midspan deflection -2 displacement transducers in the midspan section;
- The midspan steel extension -2 strain gauges placed at the midspan section (bottom of the rib);
- The applied load and support reaction -4 load cells at each end of the slab.

The test load sequence had several phases:

1. Beginning of the slab loading by application of the distributed and midspan linear load, until the load correspondent to the serviceability limit state (*SLS*) was reached (Fig. 26-a).
2. Increase of the distributed and midspan line loads until the load correspondent to the ultimate limit state (*ULS*) was reached (Fig. 26-b). At the end of this phase the distributed load reached its

Table 13 Predicted loads of the slab test for the ULS and SLS

Applied loads		Serviceability limit states	Ultimate limit states
Permanent Loads	Self Weight = 3.621 kN/m (γ= 1.35)	3.621	4.888
	Covering+Partitions = 2.86 kN/m (γ= 1.35)	2.860	3.861
Imposed Loads	Distributed = 4.0 kN/m (γ= 1.50; Ψ_1 = 0.7)	2.800	6.000
	Line load = 15 kN (γ= 1.50; Ψ_1 = 0.5)	7.500	22.500

a) Serviceability limit state b) Ultimate limit state

Fig. 26 Composite slab load phases

a) Cracks b) End slip

Fig. 27 Composite slab at the end of the test

maximum value.

3. Increase of the linear load until composite slab rupture.

In order to induce slab rupture, the displacement transducers were removed (to avoid damage) and the slab line load was increased (0.1 mm/s velocity).

Rupture was attained by bending with profiled sheet yielding, since: i) The slab presented a significant end slip and a big midspan deformation, which usually occurs in rupture by bending with partial interaction; ii) the load-deformation curve was almost horizontal at the end of the test, which also normally occurs in rupture by bending and iii) the midspan profiled sheet extension was nearly 9500 μm/m, when the profiled sheet specimens tested presented a yielding extension of 2,000 μm/m (Lopes 2005). These facts led to the conclusion that a midspan plastic hinge was being formed.

After the collapse of the slab, cracking was substantial. Fig. 27 shows bending and longitudinal shear cracks, as well as end slip. The cracks produced by longitudinal shear indicate a shear length of approximately 1.80 m.

During the three test phases - SLS, ULS and Rupture - the effectively applied load to the slab is the one mentioned in Table 14.

Table 15 presents the internal efforts (due to the applied load), the shear length and the midspan deflection for each test phase. The shear lengths were determined from the internal efforts (according to EN 1994-1-1) for the different test phases.

Since the predicted deformation did not verify the maximum allowed deformation (*L*/180), the slab had been propped during execution. The midspan deflection (indicated in Table 15) does not include

Table 14 Effective load applied to the composite slab

Load effectively applied	Serviceability limit states	Ultimate limit states	Rupture
Composite Slab Self-Weight [kN/m]	3.621	3.621	3.621
35% Slab Self-Weight + Covering + Partition + Dist. Imposed Load [kN/m]	5.463	11.065	11.065
Imposed Line Load [kN]	8.424	21.388	69.006

Note: The slab self-weight is applied. Therefore only 55% of its value was applied in ULS.

Table 15 Internal efforts midspan deflection and shear length

	Serviceability limit states	Ultimate limit states	Rupture
V_{Ed} [kN]	22.379	40.066	63.875
M_{Ed} [kNm]	26.591	50.760	98.378
L_s [m]	1.188	1.267	1.540
$\delta_{midspan}$ [mm]	3.14	18.68	-

the deformation caused by the temporary prop removal (estimated in 1.53 mm for short-term loading).

The effective resistance reserve of the composite slab, determined by the Eq. (8), concerning to the effort E_i at the ultimate limit state, is presented in Table 16.

$$R_{Resistance, E_i} = \frac{E_{Rupture} - E_{ULS}}{E_{ULS}}, \tag{8}$$

In conclusion, should be referred that the tested slab presented a longitudinal shear resistance higher than predicted, essentially due to: i) the real shear length is higher than predicted; ii) the slab was designed through the m-k method; iii) load applied in many points increases the longitudinal shear resistance (Veljkovic 1998) and iv) if the thickness increases, the longitudinal shear resistance of the slab also increases (Luttrell 1987).

5.2 Comparison between the experimental results and the analytical methods

In the analysis of the behaviour of the composite slab by the studied analytical methods, the average connection resistance values and the material properties were used, considering safety partial factors (γ_{ap}, γ_{vs} and γ_c) with unitary values.

In order to calculate the midspan deflection from the curvature of the critical section (provided by the New Simplified Method), it is necessary to integrate the curvatures presuming, in a simplified way, that the curvature displays a linear variation between the support and the midspan section (critical section). In this case, the test structural scheme is the one presented in Fig. 28 and the midspan deflection is given by Eq. (9):

Table 16 Effective composite slab resistance

Effort E_i	Effective resistance (%)
V_{Ed}	59.4
M_{Ed}	93.8

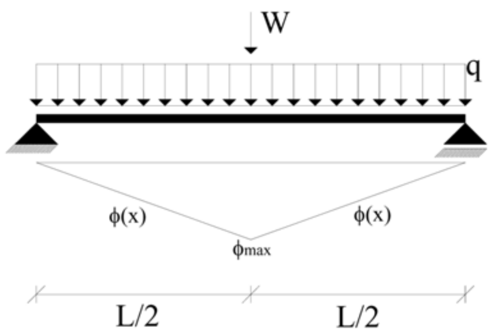


Fig. 28 Structural test scheme

$$\delta_{midspan} = \int_L (\phi(x)\overline{M})dx = \frac{1}{12}\phi \cdot L^2 \tag{9}$$

where $\overline{M}$ represents the virtual moment caused by a vertical linear load applied at midspan.

From the moment-curvature relation for the ultimate and serviceability limit states it is possible to relate the critical section moment with the midspan deflection (Fig. 29).

Short-term loading is considered for the midspan deflection calculation, according to EN 1994-1-1. When the deflection is calculated by curvature integration (*New Simplified Method*) it's enough to replace the bending moment applied to the slab, for each limit state, in Fig. 29 to determine the midspan deflection. The determined values are represented on Table 17.

Through the Table 17 analysis it is possible to verify that all analytical methods provide values for the midspan deflection closer to the measured ones for serviceability limit state load. However, the New Simplified Method provides more accurate values in this particular case.

When the ultimate limit state load is reached, the composite slab was quite cracked and the concrete component was between the linear (elastic) and the nonlinear state. Due to this fact, the deflection value

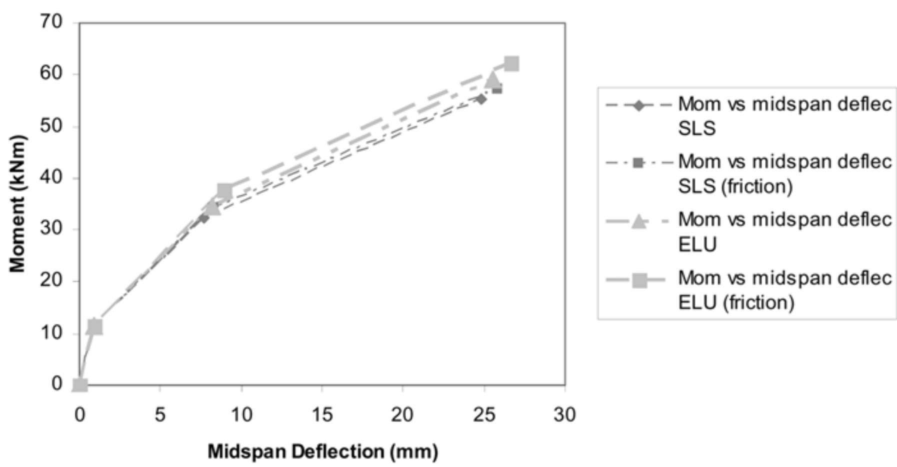


Fig. 29 Bending moment vs. midspan deflection of the slab (New Simplified Method)

Table 17 Comparison between the foreseen midspan deflection and the measured one during test

Limit states	Bending moment – without slab self weight [kNm]	Midspan deflection (mm)			
		Measured from test	New Simplified Method (Curvature integration)		EN 1994-1-1
			Without friction	With friction	
SLS	19.35	3.14	3.45	3.48	3.73
ULS	43.52	18.68	14.59	13.07	8.28

foreseen in EN 1994-1-1, calculated in elastic range, is lower than the measured one.

The New Simplified Method presents good results in the prevision of the serviceability limit state midspan deflection, because the equivalent composite section is in linear elastic state until point II. A similar situation occurred during the test of the composite slab.

The ultimate limit state bending moment occurs between Points II and III of the bending moment-midspan deflection relation. Above the Point II, the deflection obtained by the New Simplified Method is very different from the real one. However, in an ultimate limit state analysis of a structural element, the deformation is only relevant if it induces second order effects, which is not the case.

In the analysis of the composite slab until rupture, the New Simplified Method and the Partial Connection Method takes into account the additional resistance guaranteed by friction. This option was made because in this phase the support reaction is significant.

The shear length of the slab changed during the test, between the limits $L/4$ (distributed load) and $L/2$ (linear load at midspan). This variation is particularly significant from the instant that the distributed load becomes constant; this is, from the final of the ultimate limit state phase.

For the test rupture load, the shear length L_s calculated by EN 1994-1-1 is equal to 1.54 m. For this length, the New Simplified Method indicates a resistant moment of 76.49 kNm, with an equivalent steel section plastification of approximately 46.4%. This moment is 28.6% lower than the effectively applied moment in the slab. Fig. 30 presents the composite slab moment-curvature relation for shear lengths higher than 1.54 m; from this figure, it's possible to verify that the resistant moment depends on the assumed shear length. However, it is not possible to exceed the moment of 86.65 kNm (88.1% of the maximum moment applied to the slab) because the entire steel equivalent section achieved the yielding stress.

The shear length calculation according to EN 1994-1-1, in general, leads to conservative results. Indeed, the cracks induced by longitudinal shear and the New Simplified Method results (Fig. 30) indicate a shear length with a value near to 1.8 m, therefore, very different from the value of 1.54 m calculated by EN 1994-1-1.

Fig. 31 presents a partial connection diagram. The maximum resistant moment obtained by the Partial Connection Method is 87.51 kNm (conditioned by the total yielding of the steel sheet). In this case, that moment is attained for a resistant length closer to the shear length foreseen by the EN 1994-1-1, equal to 1.54 m. The longitudinal shear strength that fits the Partial Connection Method (τ_u), with or without friction, is determined for a shear length that is according to the procedure indicated in EN 1994-1-1. This can justify why the values are so close.

Both methods indicated for the calculation of the partial connection moments presents very similar maximum moments, although for very different shear lengths.

In a design situation, when only one shear length is defined, the moments determined by the two methods would be very different; for example, considering L_s = 1.54 m, the resistant moment determined

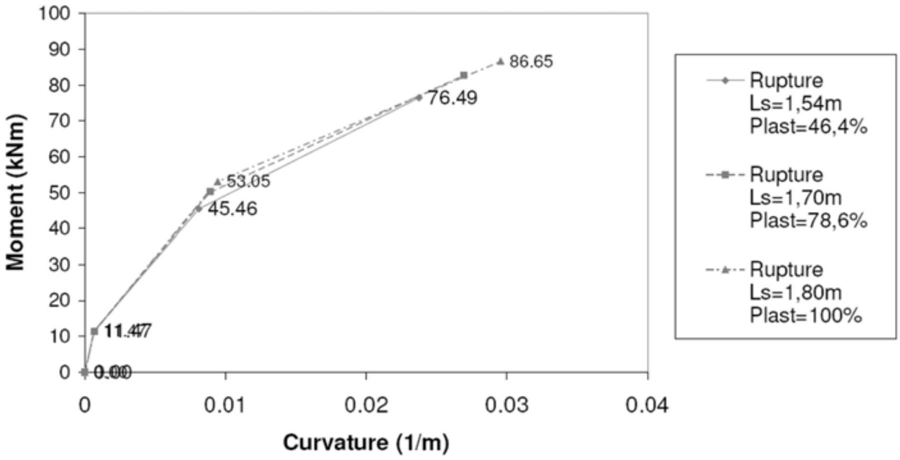


Fig. 30 Moment-curvature relation of the equivalent section of the composite slab for several shear lengths

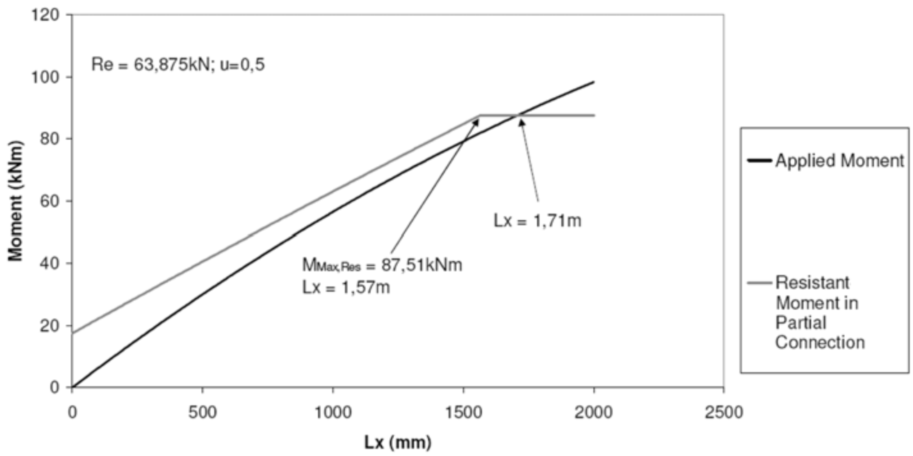


Fig. 31 Partial Connection Diagram (EN 1994-1-1) of the final composite slab

by the New Simplified Method is 14.4% lower than the resistant moment determined by the Partial Connection Method (Lopes 2006).

6. Conclusions

The experimental tests were performed in a particular composite slab configuration to obtain the parameters necessary to the application of the analytical methods for slip resistance analysis. These tests also allowed to get some conclusions about its behaviour. All the tested slabs presented a ductile behaviour; in general, the maximum load applied to the slabs was almost twice the load that causes total detachment of the concrete.

From the comparison of the tests results with the analytical methods it is possible to draw the following main conclusions: i) the New Simplified Method and the EN 1994-1-1 present realistic values for the serviceability limits state midspan deflection; ii) the maximum resistant moment obtained by the New Simplified Method is quite closer to the applied moment of the slabs subjected to two symmetrical linear loads, as long as the additional resistance guaranteed by friction is not considered; iii) in the Partial Connection Method and in the New Simplified Method the maximum resistant moment of the final composite slab was conditioned by the sheet plastification, confirming the tested slab collapse mode; iv) the Partial Connection Method and the New Simplified Method demonstrate that if the shear length increases, the resistant moment in partial connection also increases and v) on the contrary, the m-k Method indicates that the resistance decreases when the shear length increases; therefore the use of that method in slabs design, with shear lengths different from the ones that allow to determine the m and k values, should be prudent.

According the results of this research work, the method developed at the Federal Polytechnic School of Lausanne, here designated by "New Simplified Method" based on pull-out tests, can be a valid alternative to the methods of EN1994-1-1; however, this conclusion must be confirmed with further applications to real cases.

Acknowledgments

The authors would like to thank Corus Portugal, in particular to Architect Fernando Mourão, for the supply of the profiled sheets.

Thanks and recognition is also given to Professor Michel Crisinel, from the Federal Polytechnic School of Lausanne, who provided study elements essential to understand the *New Simplified Method.*

Nomenclature

b	Width of the slab
b_1, b_2, b_3	Geometrical parameters in an equivalent composite slab section
$b_{1,0}$	Width of the rib of the profiled steel sheeting
$b_{3,0}$	Width of the bottom of the concrete rib
$b_{eq,c}$	Equivalent width of the concrete in a composite slab
b_{orig}	Width of the slab for calculation
b_s	Distance between the centres of profiled sheeting ribs
d_p	Depth to the centroidal axis of the profiled sheet measured from the slab top
e	Level of elastic neutral axis
e_p	Level of plastic neutral axis
f_{cm}	Ultimate strength of the concrete
f_{yp}	Yield strength of the steel sheet
$h_{eq,c}$	Equivalent thickness of the concrete in a composite slab
h_p	Overall depth of the profiled steel sheeting
h_t, h, h_{tot}	Overall thickness of a composite slab
k	Fitting parameter of the m-k Method
l_b	Concrete blocks height
m	Fitting parameter of the m-k Method

s	Slip displacment
t_1, t_2	Geometrical parameters in an equivalent composite slab section
t_p	Thickness of the steel sheeting
A_p	Cross sectional area of the profiled sheet
C_1	Relative slip between profiled sheets and the concrete blocks in the pull-out tests
C_2	Relative slip between profiled sheets and the concrete blocks in the pull-out tests
E_{cm}	Young modulus of the concrete
$E_{Rupture}$	Force in the rupture
E_{ULS}	Force in the ultimate limite states
F	Total vertical load in a slab according EC4
P	Load
F_{max}	Maximum shear force resistance determined in the pull-out tests
F_{slip}	Shear force resistance before slip determined in the pull-out tests
F_{tot}	Total tension force in the pull-out tests
H_1	Horizontal force applied in the pull-out tests
H_2	Horizontal force applied in the pull-out tests
L	Slab span
L_o	Cantilever length of the slab near the support
L_s	Shear span
L_x	Resistant length
M_{pla}	Plastic moment of steel sheet
$M_{p,Rm}$	Sagging moment resistance
M_{test}	Maximum moment applied on the test
M	Bending moment
$\overline{M}$	Virtual moment due to a vertical linear load
N_c	Compressive normal force applied in concrete
N_{cf}	Compressive normal force applied in concrete with full shear connection
$R_{Resistance,Ei}$	Effective resistance corresponding to the effort Ei
$Slip_{Fmax}$	End slip for maximum applied load
SW_{spec}	Self weight of the specimen
$V_{l,Rd}$	Design shear resistance
V_t	Support reaction; transverse shear
V_{tk}	Characteristic value of the support reaction
W	Total vertical load
$W_{0.1\ mm}$	Load in which end slip is equal to 0.1 mm
W_{1crack}	First crack load
W_{1slip}	First end slip load
W_{2slip}	Second end slip load
$W_{L/350}$	Load for a mid-span deflection of L/350
W_t	Maximum load P applied in the test
δ	Deflection
δ_{1crack}	Mid-span deflection when the first crack occur
δ_{1slip}	Mid-span deflection when the first end slip occur

δ_{2slip}	Mid-span deflection when the second end slip occur
δ_{max}	Midspan deflection at the end of the test
$\delta_{midspan}$	Midspan deflection
δ_{Wt}	Midspan deflection for maximum applied load
ϕ	Curvature
γ	Partial safety factor
γ_{ap}	Partial safety factor for steel sheet resistance
γ_c	Partial safety factor for concrete resistance
γ_{vs}	Partial safety factor for shear connection resistance
η	Shear connection degree
μ	Friction coefficient
τ	Longitudinal shear stress
τ_{max}	Longitudinal shear strength by mechanical interlock
τ_{slip}	Longitudinal shear strength by chemical bond (before slip)
τ_u	Longitudinal shear strength ?
$\tau_{u,Rd}$	Design value of longitudinal shear strength
$\tau_{u,Rk}$	Characteristic value of longitudinal shear strength

References

Bode, H. (1990), "Design of Composite Slabs with Partial Shear Connection", *ECCS TWG 7.6 Working Group Communication.*

CEN Eurocode: Basis of Structural Design, EN 1990, *European Committee for Standardization, Brussels*, 2001.

CEN - Eurocode 4 - Design of Composite Steel and Concrete Structures - Part 1-1: General rules and rules for buildings, EN 1994-1-1, *European Committee for Standardization, Brussels*, 2007.

Crisinel, M. and Carvajal, F. M. (2002), "A new simplified method for the design of composite slabs", *Proceedings of Third European Conference on Steel Structures*, Coimbra, pp. 431-440.

Daniels, B. and Crisinel, M. (1988), "Composite slabs with profiled sheeting", *Proceedings of an Engineering Foundation Conference on Composite Construction in Steel and Concrete, ASCE*, pp. 656-662.

EN 10002 Materiais Metálicos-Ensaio de Tracção. Parte 1: Método de Ensaio à Temperatura Ambiente, *IPQ*, 1990.

Lopes, E. (2005), "Lajes Mistas Aço-Betão: Metodologias de Verificação do Corte Longitudinal", *Tese de Mestrado* (in Portuguese), Coimbra.

Lopes, E. and Simões, R. (2006), "Experimental Behaviour of Composite Slabs", *Proceedings of the XI International Conference on METAL STRUCTURES*, 21-23 June 2006 Rzeszow ? POLAND.

Luttrell, L. D. (1987), "Flexural Strength of Composite Slabs", *Composite Steel Structures-Advances*, *Design and Construction*, Elsevier Science Publishing Co., Inc.; pp. 106-116.

Patrick, M. and Bridge, R. (1994), "Partial shear connection design of composite slabs", *Eng. Struct.*, **16**(5), pp. 348-362.

Porter, M. and Ekberg, C. (1976), "Design Recommendations for Steel Deck Floor Slabs", *J. Struct. Div*, ASCE, **102**, pp. 2121-2136.

Veljkovic, M. (1998), "Influence of Load Arrangement on Composite Slab Behaviour and Recommendations for Design", *Constr. Steel Res.*, 45(2), pp. 149-178.

CC