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PREDICTION OF LONGITUDINAL SHEAR RESISTANCE OF COMPOSITE SLABS WITH PROFILE SHEETING TO EUROCODE 4

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ABSTRACT

Composite slab incorporate profile sheeting is widely used for multi-storey buildings construction throughout the world. The profile sheeting not only providing the temporarily support to the wet concrete but also formed an integral part of the composite slabs, it provides the resistance to vertical separation and longitudinal slippage between the steel concrete interface. Longitudinal shear resistance of the composite slabs is difficult to predict theoretically and the Eurocode 4 method to predict the longitudinal resistance rely on experimental testing. The most common mode of failure of the composite slab is by longitudinal shear and loss of interlocking at the steel-concrete interface. This paper presents the testing of the composite slabs in accordance to the Eurocode 4.

KEYWORDS

Composite slab, Eurocodes, Profile decking, Shear bond failure, m – k test, Longitudinal shear

INTRODUCTION

Composite slabs consisting of profiled steel sheeting are widely used in steel framed structures nowadays. Primarily, composite slab system has two major advantages over conventional reinforced concrete slabs. Firstly, the profiled sheeting provides a permanent and integral formwork for the slab during concreting. Thus, the constructional loads consisting of wet concrete can be resisted by steel deck. Secondly, it acts as tensile reinforcement once the concrete has hardened. This eliminates or significantly reduces the need for tensile reinforcement. The other form of reinforcement required is the wire mesh which is used to control temperature and shrinkage. In addition, the shape of steel deck leads to a reduced amount of concrete resulting in reduced column sizes and smaller foundation loads.

Composite beams incorporate composite slabs with profiled sheeting are an economical form of construction. This type of construction allows for long span without propping. Particularly, when deep trapezoidal metal deck is used, it results in significant reduction in the weight of concrete. Two distinct stages should be taken into account while designing the composite floor system. At the construction stage, the steel sheeting should be strong and rigid enough to support the weight of wet concrete. The profiled sheeting is subjected to the wet concrete load which is the most critical design loading for the composite slab design as the profiled steel sheeting is act as permanent formwork. Indentations or embossments and other shear transferring devices are used to ensure composite action between the steel profiled sheeting and the hardened concrete. However, when the concrete is still wet, no composite action can occur; sheeting alone carries the weight of the wet concrete and any other construction loads such as workmen, tools and storage.

The wet concrete exerts a pressure acting normal to the flanges of the sheeting. This pressure is different in the top and bottom flanges of the sheeting due to the increasing depth of the slab. The depth of concrete will be more at a place where deflection of the sheeting occurs. This increased depth of concrete due to deflection of the sheeting is termed as “ponding effect”.

At composite stage, the profiled sheeting, acting compositely with the hardened concrete will be supporting the imposed loading. The steel deck not only acts as permanent formwork but also as tensile reinforcement. The efficiency of the composite slabs depends on the composite action between the steel and the concrete. In order to achieve the required composite action and to ensure that steel deck acts as tensile reinforcement, longitudinal shear forces have to be transferred between the steel deck and concrete. Commonly, this shear transfer is achieved by the embossments or indentations on the profiled sheeting. Apart from horizontal shear forces, the imposed bending action can create vertical separation between the steel and the concrete. Therefore, the profiled sheeting must resist vertical separation as well as transfer horizontal shear forces between the steel-concrete interfaces. Both re-entrant (dovetail) and trapezoidal (open-rib) profiles are used, however the later is more common in the UK.

The shear bond characteristic depends on many factors such as the height, shape orientation and frequency of embossments, the geometry and flexibility of the profiled sheeting. The shear bond characteristic of the embossed sheeting is determined by two empirical parameters ‘m’ and ‘k’, where ‘m’ represents the mechanical interlocking between steel and concrete and ‘k’ accounts for the friction between them.

Makelainen and Sun (1999) studied the longitudinal shear behaviour of composite slabs. The parameters varied were the shapes, sizes, locations of embossments and sheeting thicknesses. All specimens failed in a brittle manner and no plastic deformation was observed. It was found that the depth of the embossment had more effect on longitudinal shear behaviour of a particular profile compared with the length and the shape of embossments. In addition, penetrated embossments improved the shear resistance of steel-concrete interface significantly. The thickness of the sheeting had a major effect on the stiffness of the profile.

Burnet and Oehlers (2001) devised a new form of push test that could predict the bond characteristics of the composite profiled slabs more accurately. The new test set up was used to perform 33 tests to investigate parameters affecting chemical and mechanical bond strengths of dovetailed and trapezoidal rib shear connectors. The variables considered were the geometry of the cross section, embossments, sheet thickness and surface treatment.

A ductile behaviour was observed in all the tests. The results showed that embossments seemed to have minor effect on dovetailed profiles; while they had a substantial effect on shear strength of trapezoidal profiles. Increase in profile sheeting thickness significantly improved the bond strength. However, debonding agent greatly reduced the bond strength. Furthermore, it was observed that chemical bond was controlled by the geometry of the sheeting rather than material properties of the steel and concrete.

Crisinel and Marimon (2004) proposed a new design method that could predict the behaviour of composite slab. This approach considered the material properties of steel and concrete, dimensions of the slab to determine the shear bond properties of the steel concrete interface from small-scale pull-out tests. With these properties in hand, moment-curvature relationship at the critical cross-section of the composite slab was obtained. The method could be applied to both ductile and brittle type of slab failure.

The new simplified method calculated the load carrying capacity of composite slabs with the help of three phases moment-curvature relationship at the critical cross section. Although, this method can be used successfully for calculating bending and vertical shear resistance in composite beams and slabs, it cannot estimate longitudinal shear resistance of composite slabs for which full testing is required.

Ganesh *et al.* (2005) proposed a simplified approach for the design of composite slabs. They used a slip block test to obtain moment resistance of composite slab based on partial shear design method. The slip block consisted of a piece of profiled sheeting spot-welded to steel base plate. The top surface of concrete contained two steel plates with roller bearings in between them. A horizontal force was applied to the face of the specimen while keeping vertical force constant. This test arrangement did not take into account effect of bending that is present in full-scale tests.

This paper presents the details of the experimental investigation conducted on the composite slabs and the evaluation of m-k values for the profile sheeting in accordance to Eurocode 4 (2004).

EXPERIMENTAL STUDIES

The experimental investigation was divided into two groups of three tests. Each group was tested for both long and short shear span loading. All the tests were carried out in accordance with Annex B of Eurocode 4 (EC4). The composite slab specimens were simply supported with two equal line loads placed symmetrically at quarter span distance from the centre line of supports. In each group, one of the three specimens was subjected to static or monotonic loading until failure to determine the level of cyclic loading for remaining two tests in the group. For the cyclic test, the slabs were subjected to 5000 cyclic loading followed by test to failure.

Two groups of three tests were carried out on composite slabs with trapezoidal profiled sheeting. The length of the specimens was 5000 mm and 3000 mm respectively. The long slab had a shear span of 1200 mm; while the short slab had a shear span of 700 mm. Tests were performed on simply supported 2-points loading conditions. Long length specimens were identified by label of ‘CSL’ while the short length specimens were recognised by the abbreviation of ‘CSS’. The experimental set up for the composite slab is shown in Figures 1 and 2.

Load was applied by a 10T hydraulic jack via transverse and longitudinal spreader beams. In this way, two equal and concentrated line loads were applied at the quarter and three quarter point on the composite slab. The span of long and short composite slab specimens was 4800 mm and 2800 mm respectively. The mid-span deflection and end-slip at both ends were measured using LVDTs. Crack inducers were cast in place at the loading positions. Figure 3 shows the specimen before concrete casting.

LVDTs were attached to both ends of the composite slab in order to measure the relative slip between the concrete and the steel deck. Mid-span deflection was measured at the centre of the span in the central trough of the profiled sheeting. Load was applied and measured through a load cell placed at the centre of the specimen. Reactions at supports were measured with the help of two load cells placed under the support plate at each ends. In addition, the self-weight of the specimen and the weight of spreader beams were measured as reactions at the supports before load application.

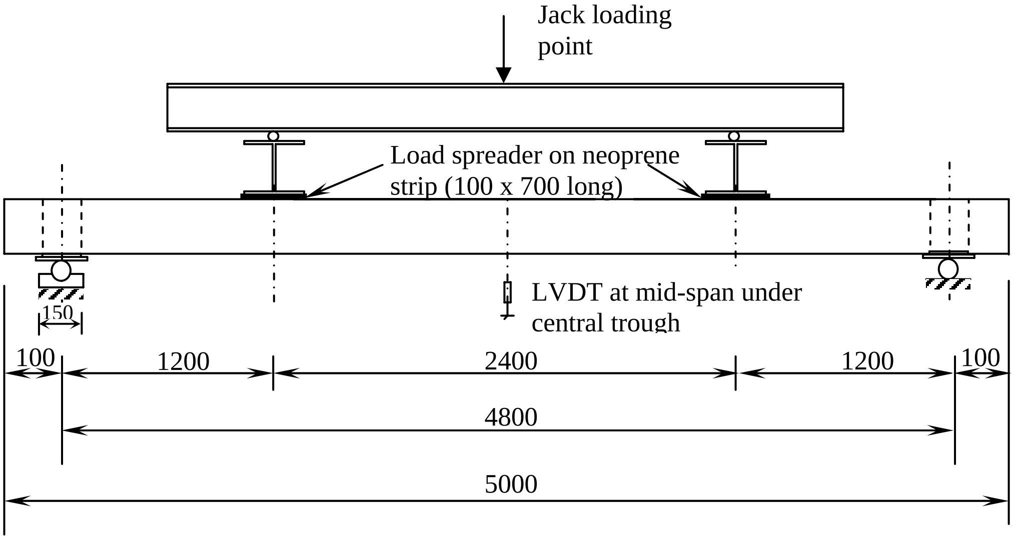

Figure 1: Test arrangement for the long-span composite slabs

Figure 2: Test arrangement for composite slab tests

For the *m-k* test, two groups of three specimens were tested; the first specimen was subjected to static loading until failure in order to determine the loading range for the two subjected to cyclic testing. The cyclic test consisted of two stages. For the initial stage, the load was applied for 5000 cycles that ranged from 20% to 60 % of the failure load. The purpose of cyclic loading was to break any chemical bond between the profiled sheeting and the concrete. Chemical bond is formed as a result of chemical adherence of cement paste to the steel sheeting. Slip is initiated as soon as this bond is broken. According to EC4, the load should be applied for 5000 cycles in a time not less than 3 hours. However, it has been reported by Wright *et al* (1987) that there is negligible effect of the cyclic loading on the load carrying capacity of the composite slabs. After completion of the initial stage, loading is applied to the composite slab until failure occurred.

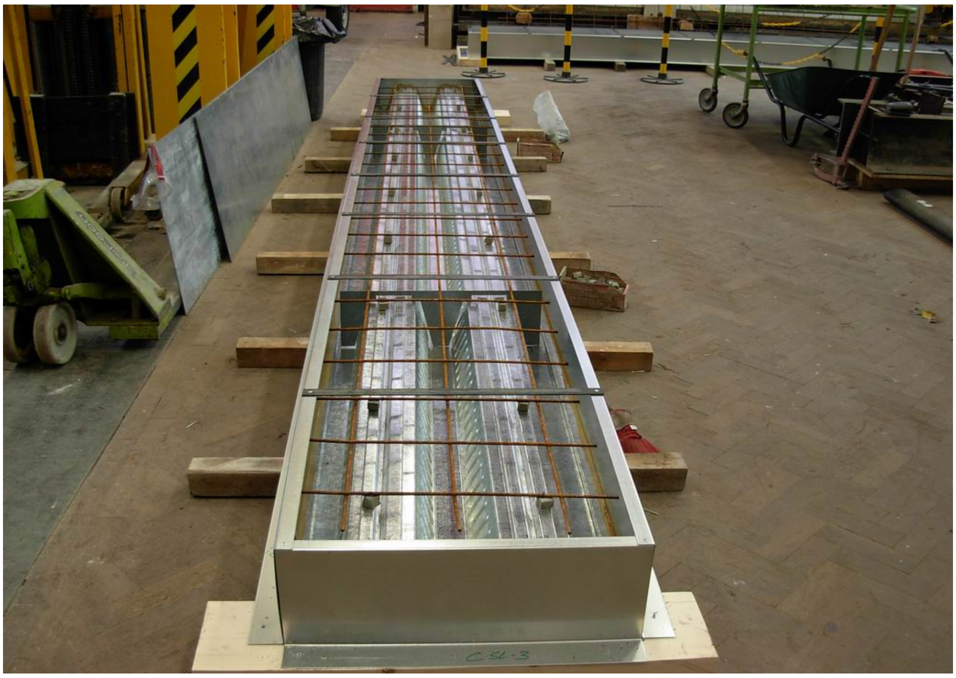

Figure 3: Specimens before concrete casting

TEST RESULTS

Six composite slab tests were carried out, three long span and three short span. For each group, static test was performed following by the cyclic tests. The test results are explained as follow.

Static Test

The test specimens consisted of two groups with a span length of 4800mm and 2400mm. The shear span, which is defined as the distance from the centreline of supports to point of application of load, was equal to 1200 mm and 700mm respectively.

Prior to load application, the specimen was placed on the supports so that self-weight of the specimen can be measured, the weight of the longitudinal and transverse spreader beams were measured in the same way. The load was applied gradually in increments under deflection control and the applied load was recorded for every 2 mm central deflection increments. The central deflection and end slips were measured with the LVDTs placed under the centre of the specimen and at the ends of the specimen. The load vs. mid-span deflection curve is shown in Figure 4. In this curve, the load included the self-weight of the specimen, the weight of spreader beams and the applied load. The central deflection increased as soon as the load was applied. Shear cracks near the loading points were first observed. Figure 5 shown the formation of the longitudinal shear cracks within the shear span of the test specimen.

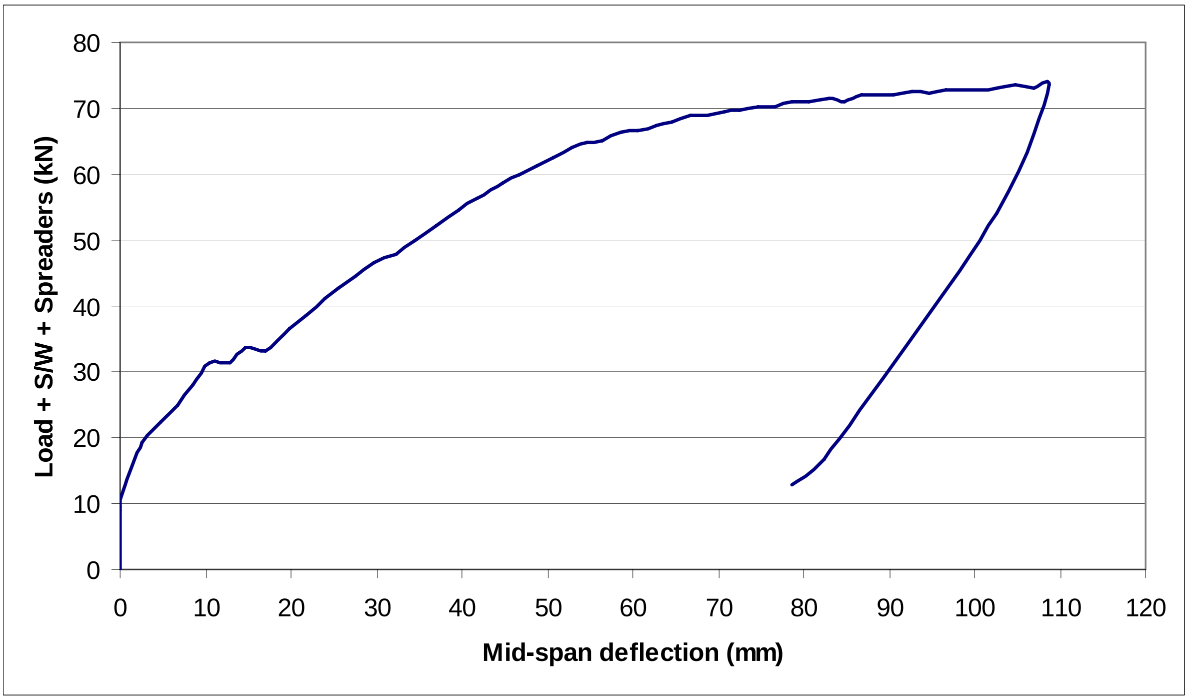

Figure 4: Static test for the long-span specimen

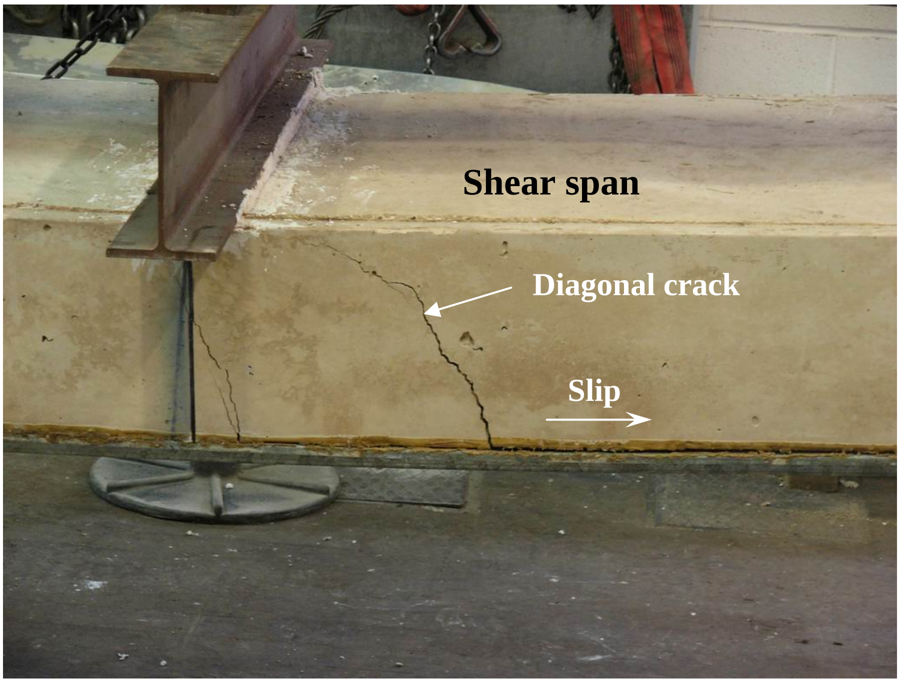

Figure 5: Shear crack and longitudinal slip near the shear span

Cyclic Test

The test arrangement for the cyclic tests was similar to static test except that it was subjected to an initial cyclic loading. The composite slab was subjected to cyclic loading in order to break chemical bond between the steel and the concrete, followed by a gradual static loading until failure. The subsequent static test would give the real indication of mechanical bond formed by indentations or embossments on the profile sheeting.

The loading range for the cyclic tests was determined from the static loading test conducted earlier. The cyclic load was applied in the range of 20% to 60% of the failure load. Figure 6 shows the load vs. mid-span deflection of the cyclic test. The test results for the long-span and short-span specimens are given in Table 1.

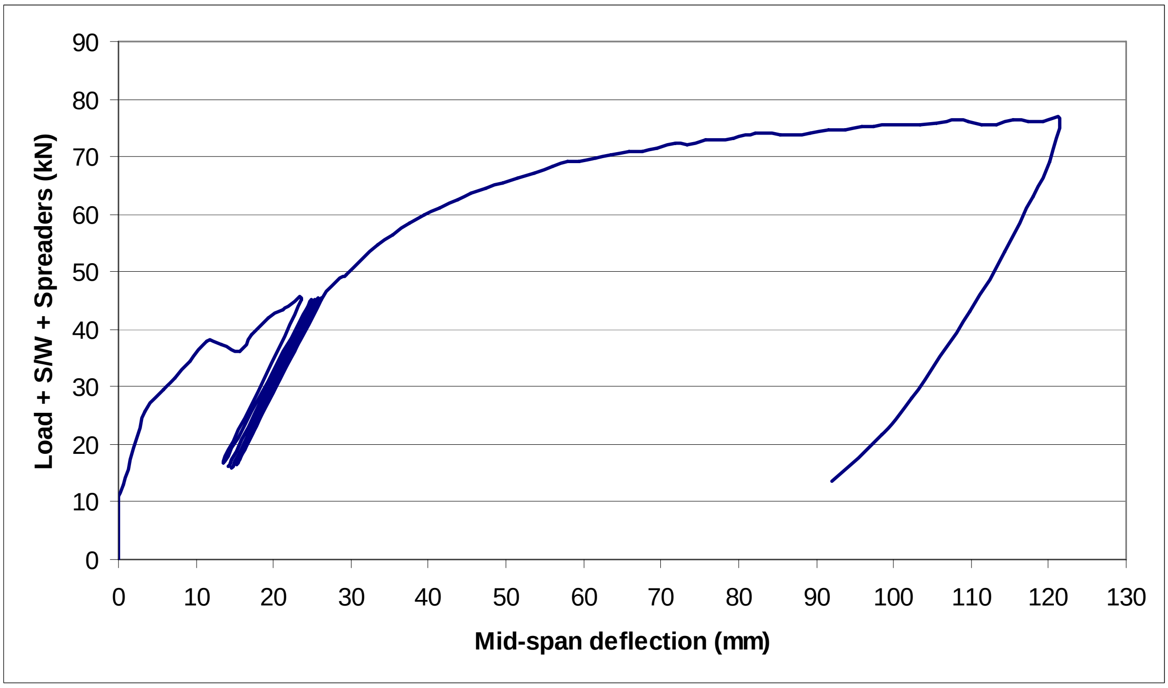

Figure 6: Cyclic test for the long-span specimen

Table 1: Summary of test results from full scale composite slab tests

Group	**Test**	**Type of loading**	**Load at first crack (kN)**	**Failure load (kN)**	**Mode of failure**	**Mid-span deflection at failure (mm)**	**Maximum end slip at failure (mm)**
Long Span	**CSL-1**	Monotonic	31.3	73.57	Ductile shear bond failure	108.7	5
	CSL-2	Cyclic	34.9	76.4	Ductile shear bond failure	115.75	6.4
	CSL-3	Cyclic	37.9	76.46	Ductile shear bond failure	121.36	5.63
Short Span	**CSS-1**	Monotonic	40.5	119.84	Ductile shear bond failure	60.32	8.2
	CSS-2	Cyclic	41.4	127	Ductile shear bond failure	60	6
	CSS-3	Cyclic	46.45	126.60	Ductile shear bond failure	61.5	5.8

THE SHEAR BOND (*M-K*) METHOD

This method uses the full-scale test results to establish the longitudinal shear capacity of the composite slabs. These two constants *m* and *k*, which have dimensions of stress, are used to determine the design resistance of composite slab against the longitudinal shear. This method can be used for composite slabs with either ductile or brittle longitudinal shear behaviour.

The shear bond characteristics of the embossed profiled sheeting are rated by two empirical constants *m* and *k*. The parameter *m* corresponds to the mechanical interlocking between steel and concrete; while *k* represents the friction between them. In this method, the design *vertical* shear resistance is determined from the following equation according to Eurocode 4:

$$V_{l,Rd} = \frac{bd_p}{\gamma_{VS}}\left(\frac{mA_p}{bL_s} + k\right) \tag{1}$$

where,

$V_{l,Rd}$	=	the design *vertical* shear resistance
b	=	width of slab in mm
d_p	=	distance between the centroidal axis of the profiled steel sheeting and the extreme fibre of the composite slab in compression
A_p	=	the nominal cross-sectional area of profiled sheeting in mm^2
m,k	=	design values for the empirical factors in N/mm^2 obtained from slab testing
L_s	=	the shear span in mm
γ_{vs}	=	the partial safety factor for the ultimate limit state, recommended value is 1.25

The equation (1) can be rearranged to form a straight line equation in the form of $y = mx + c$ as shown in equation (2).

$$\frac{V_{l,Rd}}{bd_p} = m\frac{A_p}{bL_s} + k \tag{2}$$

In accordance to Eurocode 4, the design values of *m* and *k* are determined from the series of the full scale tests, where the results are given in Table 2. Plot with $\frac{V_t}{bd_p}$ on the y-axis verses $\frac{A_p}{bL_s}$ on the x-axis is shown in Figure 7.

The values of the representative experimental shear force V_t depends on the behaviour of the composite slabs. If the behaviour is ductile, V_t should be taken as 0.5 times the value of the failure load, W_t and in case of brittle behaviour, this value should be reduced by 20%. Eurocode 4 states that composite slabs may be considered as ductile if the failure load exceeds the load at the end slip of 0.1 mm by more than 10%, otherwise, it is a classified as brittle failure. The failure load is taken as maximum load with mid-span deflection exceeded L/50, where L is span of the slab.

The test results for long specimens (Region A) and short specimens (Region B) are plotted. The characteristic value is obtained by taking the minimum value in each group and reduced by 10%. The design relationship is established by the straight line passing through these characteristic values for Region A and Region B.

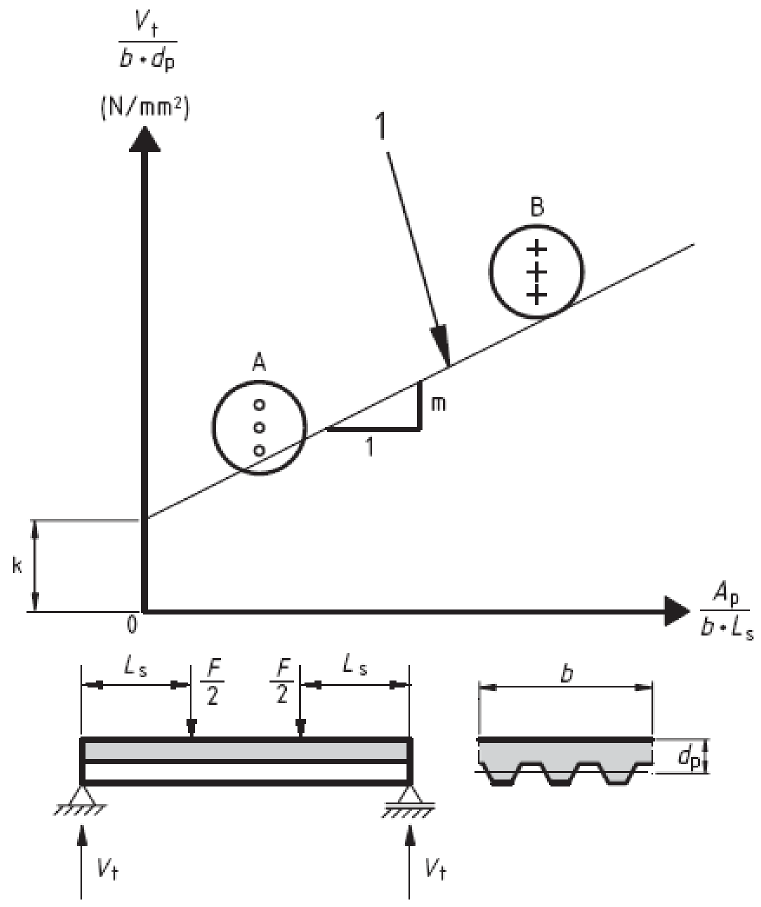

Figure 7: Evaluation of test results (BS EN 1994-1-1:2004 Annex B)

Table 2: *m*-*k* method

Group	**Ref**	**Failure load (N)**	**V_t (N)**	**b (mm)**	**d_p (mm)**	**A_p (mm^2)**	**L_s (mm)**	$\frac{V_t}{b.d_p}$	$\frac{A_p}{b.L_s}$
Long Span	**CSL-1**	73570	36785	630	135	1791	1200	0.4325	0.002369
	CSL-2	76400	38200	630	135	1791	1200	0.4491	0.002369
	CSL-3	76460	38230	630	135	1791	1200	0.4495	0.002369
Short Span	**CSS-1**	119840	59920	630	135	1791	700	0.7045	0.004061
	CSS-2	127000	63500	630	135	1791	700	0.7466	0.004061
	CSS-3	126600	63300	630	135	1791	700	0.7443	0.004061

The evaluation of the test results is presented in Table 2 with the *m*-*k* curve shown in Figure 8. The values of the empirical parameters *m* and *k* are determined as 140 and 0.05 respectively. Once the design values of *m* and *k* are obtained, these can used to design other slabs whose length and thickness lie between the two test groups using Equation (1).

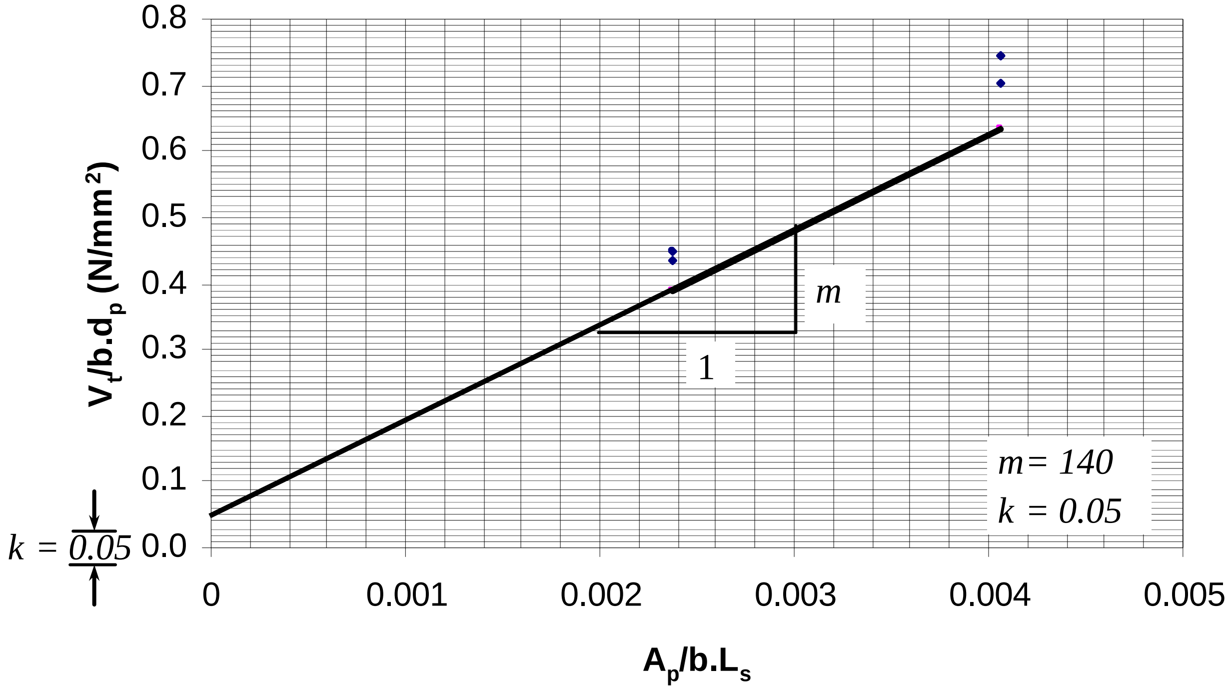

Figure 8: The *m-k* curve for composite slab

CONCLUSIONS

This paper presents the testing of the composite slabs and evaluation of the longitudinal shear capacity of the composite slabs with profile sheeting in accordance to the Eurocode 4. The long-span specimens showed only horizontal slip at the ends when failure occurred. While, failure in short-span specimens was accompanied by horizontal slip at the ends, vertical separation between the steel and the concrete and local buckling of the profiled sheeting near the supports.

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