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Determining longitudinal shear resistance of the steel-concrete composite slab by the *m-k* semi-empirical method

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KEYWORDS

Longitudinal shear resistance
The m-k semi-empirical method
Perfobond shear connector
The relative slip
Shear capacity

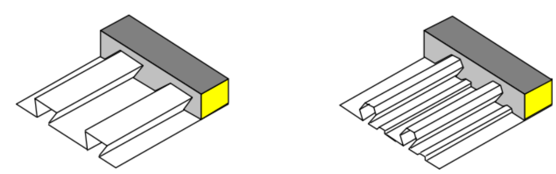
ABSTRACT

The failure of the steel-concrete composite slab may happen at the interface of the steel sheeting profile and the concrete slab when the longitudinal shear force exceeds the longitudinal shear resistance. The longitudinal shear resistance of the steel-concrete composite slab depends on the sheeting type and the dimensions of the slab section. Some methods have been used to enhance the longitudinal shear resistance, such as mechanical anchorage, frictional interlock, frictional interlock, … and so on. In this study, the perfobond shear connectors were used to improve the longitudinal shear resistance to restrain the relative slip between the sheeting profile and the concrete slab. The longitudinal shear resistance is determined by a standardized semi-empirical m-k method. The bending moment capacity obtained from the bending test was also compared to the predicted plastic moment resistance.

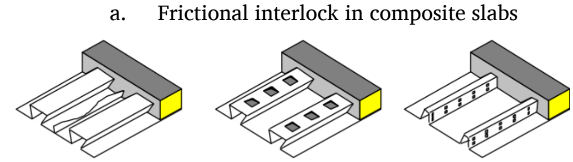
1. Introduction

The shear connection has an important role in the steel-concrete composite structure. This compounds the structural steel and the concrete slab to act together. Many types of shear connections have been applied in practice and study. The perfobond shear connection is one among these. The shear perfobond connection has been used to prevent the relative slip between the structural steel and the concrete slab in the steel-concrete composite structures. This perfobond shear connection has been widely studied with steel-concrete composite beams. Many researchers studied this kind of shear connector [1, 2, 3, 4, 5, 6, 7, 8, 9]. These studies were conducted to investigate the effects of parameters on the structural behavior of the perfobond shear connection. The parameters include the dimensions of perfobond, the number of steel bars through the perfobond holes, the compressive strength of the concrete, etc. The structural behaviors are the perfobond shear resistance, the relative slip between the structural steel and the slab concrete slab, and the failure mode by push-out tests. Some authors proposed formulas to determine the shear resistance of the perfobond shear connector. The other authors studied T-perfobond [10, 11, 12] and Y-perfobond [13] to enhance the shear resistance of the connection and reduce the relative slip between the structural steel and the concrete slab. Push-out tests with many small specimens are often carried out to determine the longitudinal shear resistance of the shear connection.

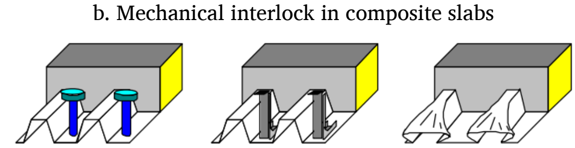
The profiled sheeting should be able to transfer longitudinal shear to concrete through the interface to ensure the composite action of the composite slab. The adhesion between the steel profile and concrete is generally not sufficient to create composite action in the slab. Thus, an efficient connection is achieved with one or several of the following, as shown in Figure 1 [14].



a. Frictional interlock in composite slabs



b. Mechanical interlock in composite slabs



c. End anchorage for composite slabs

Figure 1. Types of interlocks [14].

The longitudinal shear resistance of the steel-concrete composite slab is determined by a standardized semi-empirical method called the m-k method originally proposed by Porter and Ekberg [14]. The factors *m* and *k* are obtained from standardized full-scale tests. The longitudinal shear resistance is determined by the formula below:

$$V_{L,Rd} = b d_p \left(m \frac{A_p}{b L_s} + k \right) \frac{1}{\gamma_{VS}} \tag{1}$$

where k and *m* in N/mm²

- b the width of the slab
- d_p the average depth of the composite slab
- A_p the area of the sheeting
- γ_{VS} safety factor

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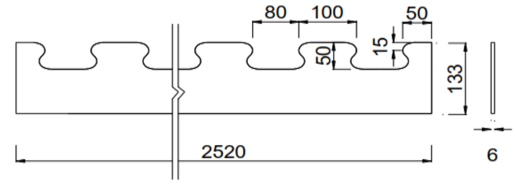
The *m* and *k* values depend on the sheeting type and the dimensions of the slab section and are generally given by profiled steel manufacturers [14].

In this study, the steel-concrete composite slab was fabricated from the concrete slab and plain profiled steel sheeting. The perfobond shear connectors were used against the longitudinal shear. The *m-k* semi-empirical method was carried out to determine the longitudinal shear resistance of the composite slab.

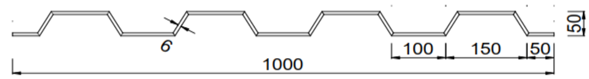
2. Test program

2.1. Specimens

The *m-k* method specimen is shown in Figure 2. The dimensions of the specimen are 1000 mm in width and 180 mm in height. The dimensions of the perfobond shear connector and the profiled steel sheeting are shown in Figure 2. The profiled steel sheeting was made from a plain steel plate of 6 mm in thickness, 1150 mm in width, and 2650 mm in length. The area of the profiled steel sheeting was 6900 millimeters square. Each perfobond hole also has one steel bar of 12 mm in diameter through the hole. The perfobond shear connectors were attached to the steel sheeting profile along the length of the specimen, as shown in Figure 3. Figure 4 presents some pictures of specimen fabrication. The parameters of specimens are presented in Table 1.

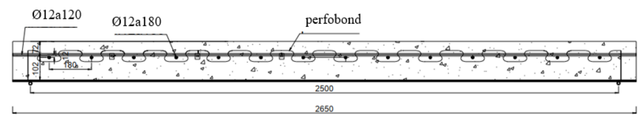


a. Perfobond shear connector

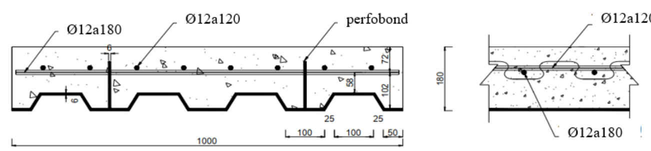


b. Profiled steel sheeting

Figure 2. Configuration of perfobond shear connector and profiled steel sheeting.



a. Section of specimen

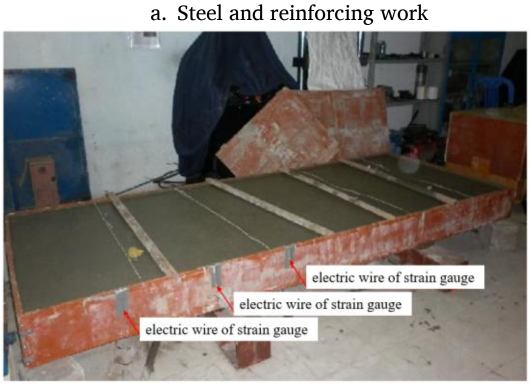


b. Detail of specimen

Figure 3. Specimen of *m-k* method.

a. Steel and reinforcing work

b. Formwork



c. After concreting work

d. Installation of LVDT

Figure 4. Specimen fabrication.

Table 1. The parameters of specimens.

Specimen	Area of dowel section	Concrete	Steel bar	Quantity	Shear span
S1	4490 mm^2	B25	$8\phi12+13\phi12$	1	833 mm
S2	4490 mm2	B25	$8\phi12+13\phi12$	1	625 mm

2.2. Material properties

2.2.1 Concrete

The concrete used for the specimens is B35. The aggregate gradation is shown in Table 2. The concrete was cured in 28 days and tested in compliance with TCVN 3118:2022 [15]. The concrete compressive strength test was carried out simultaneously with the *m-k* method test. The test results of concrete compressive strength are shown in Table 3.

Table 2. The aggregate gradation for 1 m^3 concrete.

Material component	Unit	Quantity
Saigon cement PC50	kg	385
Sand	kg	760
Stone 1×2 (Dmax = 25 mm)	kg	1040
Water	littre	200
Addition agent (MAPEI)	kg	3.7

Table 3. Mechanical characteristics of concrete.

Compressive strength f_{ck}	(MPa)	35,5
Elastic modulus	(MPa)	29×10^3
Elastic strain	ε_{elas} (‰)	1.8
Compressive strain limit	ε_{limit} (‰)	2,24

2.2.2. Profiled steel sheeting, perfobond steel, and reinforcement

The profiled steel sheeting and perfobond steel used in these tests is CT34. The steel bars and longitudinal reinforcement with 12 mm in diameter. The mechanical characteristics of these materials are presented in Table 4.

Table 4. Mechanical characteristics of reinforcement and hot-rolled steel.

Quantity	Steel bar and longitudinal reinforcement	Steel sheeting profile and perfobond steel
Yield strength (MPa)	330	250
Ultimate strength (MPa)	500	390
Elastic modulus (MPa)	200×10^3	200×10^3

2.3 Test setup

2.3.1 Test models

The *m-k* method test was carried out on two large-scale specimens. The m-k method test was conducted on bending four-point models complying with Eurocode 4 [16], as shown in Figure 5. LVDTs (Linear Variable Displacement Transducer) LVDT1, LVDT2, LVDT3, and LVDT4 were placed along the specimen length to measure the deflection of the slab. Strain gauges SG1, SG2, and SG3 were attached to perfobond shear connector to determine the strain of perfobond. A strain gauge SG4 was attached to the top surface of the slab to measure the strain of the concrete os slab. LVDT6, LVDT7, and LVDT8 were placed to measure the relative slip between the profiled steel sheeting and the concrete slab. The specimen was installed into the test frame, as shown in Figure 6.

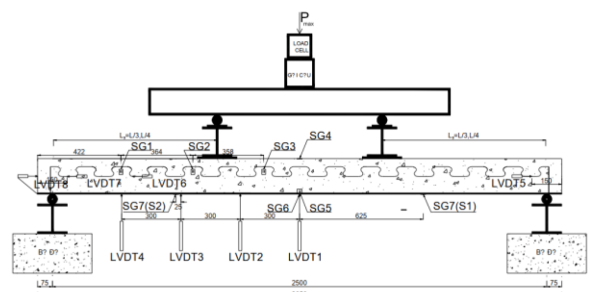


Figure 5. Test model.

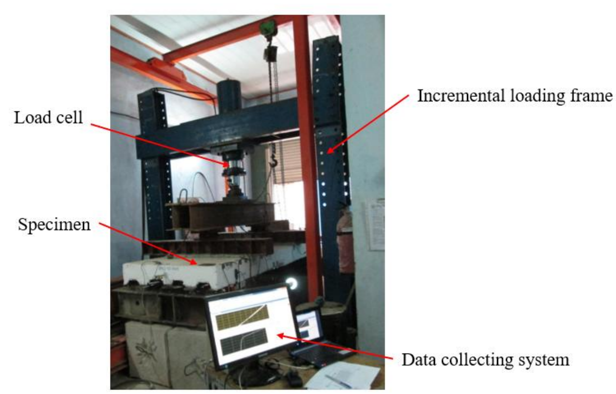


Figure 6. Test setup.

2.3.2 Incremental loading process

The incremental loading process was performed complying with Eurocode 4 [16]. This procedure had 3 phases, as shown in Fig. 7.

- Phase 1: Increasing load from 0 to 40% failure load (P_{max}), and then repeating 2 times.

- Phase 2: Increasing load from 10% P_{max} to 40% P_{max}, and then repeat 25 times. This stage is to eliminate the adhesive force, friction, and residual strain of testing.

- Phase 3: After ending phase 2, increase load from 10% P_{max} to failure load, continue increasing load until the load remains 90% P_{max}, and stop testing.

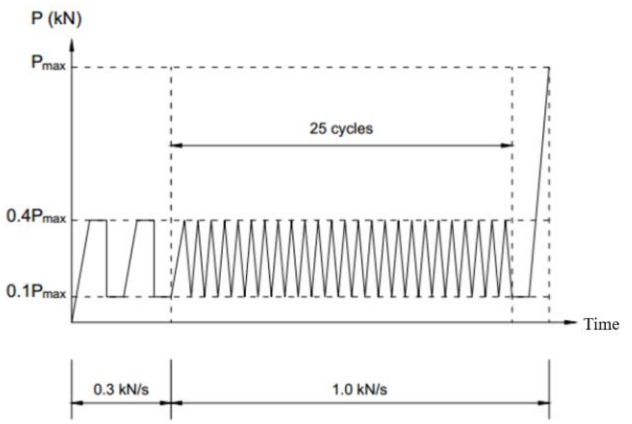


Fig. 7 Incremental loading process.

3. Test results and discuss

3.1 Test results

The test results of the m-k method are presented in Table 5 with values of ultimate load and the deflection of the steel-concrete composite slabs.

Table 5. Test results.

Specimen	Failure load	Deflection			
	P_{max}	LVDT1	LVDT2	LVDT3	LVDT4
	kN	mm	mm	mm	mm
S1	392.65	51.063	49.734	39.716	22.119
S2	621.84	38.617	38.285	34.513	23.559

3.2 Failure mode

Two specimens' failure modes occurred in the tension region, as illustrated in Figure 8. Cracks were initiated at the bottom of the slab and then developed to the upper side when the load increased.

Figure 8. Failure mode.

3.3 Longitudinal shear resistance $V_{L,Rd}$

Table 6 presents the parameters of the specimens and the value V_t getting from test results. These values are used for the formula (1). The relation between $y = V_t/bd_p$ and $x = Ap/bL_s$ is plotted in Figure 9. The equation has the form:

$$y = 0.19x + 0.9 \quad (2)$$

Table 6.

Specimen	V_t	b	d_p	A_p	L_s	$y = \frac{V_t}{bd_p}$	$x = \frac{A_p}{bL_s}$
	kN	mm	mm	mm^2	mm	N/mm^2	
S1	196.33	1000	155	6900	833	1.267	0.008
S2	310.92	1000	155	6900	625	2.006	0.011

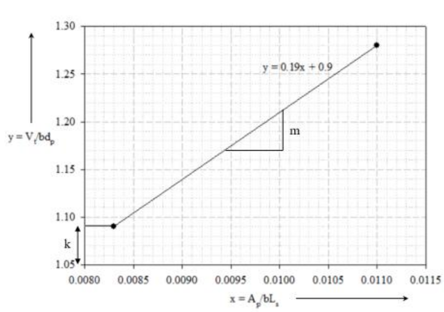


Figure 9. Derivation of *m* and *k* from test data.

Since the value of k is 0.9 N/mm^2 and m is 70.37 N/mm^2.

Substitute all values above into equation (1), the longitudinal shear resistance of the slab is:

$$V_{L,Rd} = bd_p\left(m\frac{A_p}{bL_s} + k\right)\frac{1}{\gamma_{VS}}$$

$$V_{L,Rd} = 1000 \times 155\left(70.37\frac{6900}{1000\frac{2500}{4}} + 0.9\right)\frac{1}{1.0} = 259917\ N \approx 259.92\ kN$$

3.4 The plastic moment resistance of the composite slab

Determine the bending capacity of the steel-concrete composite slab:

Because N_{cf} = 3922.75 kN > N_{pla} = 1725 kN, the neutral plastic axis passes through the concrete slab, as shown in Figure 10.

Let x_{pl} be the distance from the top surface of the concrete slab to the neutral plastic axis:

$$x_{pl} = \frac{N_{pla}}{0.85 f_{ck} b} = \frac{1725}{0.85 \times 35.5 \times 1000} = 57\ mm < h_c = 130\ mm$$

Therefore $z = d_p - x_{pl}/2 = (180 - 25) - 57/2 = 126.5$ mm

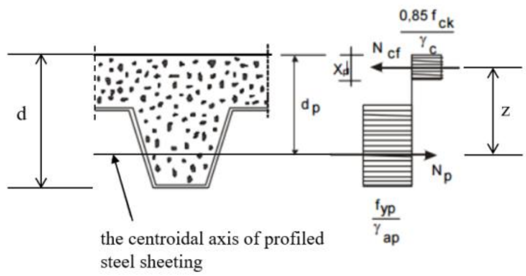


Figure 10. Stress distribution in the composite slab.

The the predicted plastic moment resistance of the composite slab is:

$$M^{+}_{pl.Rd} = N_{pla}z = 1725 \times 126.5 = 218212.5\ Nmm \approx 218.21\ kNm$$

Table 7. Comparison of the test results with the predicted results.

Specimen	P_{max}	V_t	L_s	$M_{Rd,\ test}$	$M_{Rd,\ predict}$	$\frac{M_{Rd,test}}{M_{Rd,predict}}$
	kN	kN	mm	kNm	kNm	%
S1	392.65	196.33	833	163.54	218.21	74.94
S2	621.84	310.92	625	194.33	218.21	89.06

4. Conclusions

The experimental study of bending steel-concrete composite slabs was conducted to determine the longitudinal shear resistance of the perfobond shear connectors and the bending moment capacity of the steel-concrete composite slabs. The test results show that:

The location of the applied load affects the failure load of the steel-concrete composite slabs. The failure moment of specimen S1 is 163.54 kNm (about 74.94% of the predicted plastic moment resistance), and that of specimen S2 is 194.33 kNm (about 89.06% of the predicted plastic moment resistance).

The longitudinal shear resistance of the perfobond shear connectors determined by the semi-empirical m-k method equals 259.92 kN. This value is not great enough for the perfobond shear connectors to achieve the full shear connection degree, so the failure moment resistances are smaller than the predicted plastic moment resistance.

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