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BEHAVIOUR AND LOAD BEARING CAPACITY OF COMPOSITE SLAB ENHANCED WITH SHEAR SCREWS

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Abstract: Horizontal shear interaction between profiled steel sheeting and concrete in composite slab is obtained through various means, such as frictional resistance due to indentation or embossment in the sheeting, interlocking at the steel and concrete interface resulting from curvature and shape of the sheeting profile under bending, and anchorage devices such as welded shear studs and crippled sheeting at the end of the span. Permanent end pour stops may provide some restraining effect to the slipping of the concrete, and hence may enhance the composite action. Despite the use of many types of devices, most reported test results of typical length composite slabs still exhibit partial shear interaction. This paper reports the enhancement of the horizontal shear interaction at the concrete-profiled steel sheeting interface of composite slab by using shear screws. Six full scale bending tests were conducted of which three specimens with different slenderness were enhanced with self drilling screws while another three were without screws. The test results show that the failure mode of composite slab can be improved to ductile type and the load carrying capacity can be increased by the presence of the shear screws. The load performance of the slab is also affected by the slenderness, which is the ratio of shear span to effective depth.

Keywords: Composite slab, horizontal shear bond, partial shear, bending test, shear screw

1. Introduction

A composite slab comprises of ordinary structural concrete and cold-formed profiled steel sheeting is widely used in steel framed buildings as floor system. The profiled steel sheeting serves as a form for the concrete during the construction stage and permanently acts as positive reinforcement during service. The inherent advantages of using profiled steel sheeting composite slabs have been attributed to easy construction, reduced weight, economical and sufficiently strong for its intended use.

In most cases, the concrete-steel interaction or better known as horizontal shear bond at the interface of the steel sheeting and concrete governs the behaviour and strength of a composite slab (Schuster, 1973; Johnson, 1994). Insufficient horizontal shear resistance will result in the slippage of the concrete against the steel deck under bending. At this point, the composite slab is under the partial shear interaction mode.

Frictional resistance due to indentation or embossment in the sheeting, interlocking at the steel and concrete interface resulting from curvature and shape of the sheeting profile under bending, anchorage devices such as welded shear studs and crippled sheeting at the end of the span are the known factors that influence horizontal shear bond between the profiled steel sheeting and the concrete. Veljkovic (1996) noted that the degree of interaction between the two materials affects the shear flow and strain distribution of the members, hence influences the structural performance such as strength, stiffness and failure mode. De Andrade et. al. (2004) conducted experiment on composite slab by installing self-drilling screws on the top flange of the profiled steel sheeting. The use of self-drilling screws was proved to be very efficient as a positive means of shear bonding between the steel sheeting and the concrete. The ultimate load and the stiffness of the specimen with screws were increased.

The objective of this paper is to investigate the behaviour and load carrying capacity of composite slabs enhanced with shear screws at the interface of the steel sheeting and the concrete. The study was carried out by conducting full scale bending test on the slab specimens made with trapezoidal shape cold formed steel deck and structural concrete.

2. Experimental Programme

2.1. Description of the specimen

A total of 12 full scale composite slabs made of trapezoidal shape cold-formed steel deck and normal weight concrete were built and tested in this study. Three different parameters were considered, with two specimens were built for each parameter. The cross section of the steel deck is shown in Figure 1 and the deck thickness, cross section area, bending and material stiffness are shown in Table 1. Three sets of the specimens were attached with hexagon head self drilling screws. The screw details are depicted in Figure 2 and the steel deck being attached with the screws is shown in Figure 3. The screws were drilled at 150 mm at the bottom flanges in a staggered position along the longitudinal length of the deck. Wire mesh of 3.4 mm bars at 152 mm spacing was provided in each slab for shrinkage and temperature reinforcement. The deck was fully supported during construction as it was laid on the floor during concrete pouring. Three sets of identical slab specimens but without screws were also built and tested, for comparison purpose. The dimensions and test parameters of the composite slab specimens are listed in Table 2.

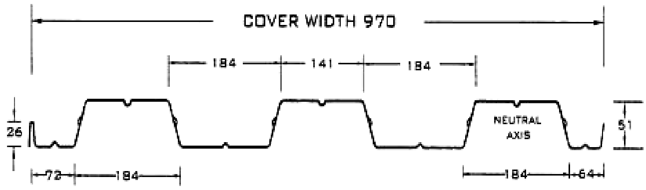

Figure 1: Geometric cross-section of SDP-51 sheeting

Table 1: Properties of the profiled steel sheeting

Thickness (mm)	Area (mm^2)	Weight (kg/m)	Cover width (mm)	Moment of inertia (mm^4)	Yielding strength (N/mm^2)
1.0	1261	10.56	970	448229	550

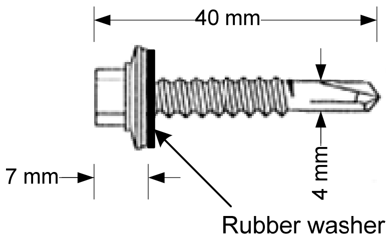

Figure 2: Self drilling screw used to enhance the shear bond

Figure 3: Steel deck with screws drilled from the bottom side (left) and a view from the top side (right)

Table 2: Composite slab specimen dimensions and details

Specimen ID	Span, L (mm)	Width, b (mm)	Concrete Thickness, d (mm)	Concrete effective depth, d_p (mm)	Shear span, L_s (mm)	Slenderness, L_s/d_p	Screws at the steel-concrete interface
C1	2300	970	150	125	600	4.8	No
C2	2900	970	150	125	750	6.0	No
C3	2900	970	100	75	750	10.0	No
S1	2300	970	150	125	600	4.8	Yes
S2	2900	970	150	125	750	6.0	Yes
S3	2900	970	100	75	750	10.0	Yes

2.2. Material properties

The compressive strength of the concrete was determined by compression test according to BS EN 12390-3 (2002). The average cube strength was 29.5 MPa. The yield strength of the profiled steel sheeting according to the manufacture's brochure was 550MPa.

2.3. Test procedure

Bending test was conducted by applying two line loads as shown in Figure 4. The specimens were supported by pin and roller type supports with an overhang of 50 mm at both ends. Static load was applied by a hydraulic ram, jacked against a reaction frame. The point load from the ram was transmitted to the specimen by means of distribution beam and then spread onto the slab as line load by spreader beams. The line loads were positioned at $L/4$ from the support, which is the shear span, L_s, as defined by Eurocode 4 (2004). The specimen length was measured from centres of supports. The load was recorded by a load cell. Mid-span deflection and the relative end slip were recorded by LVDTs. Load, deflection and end slip data were recorded at each load increment until failure. The failure was determined when load increment was no longer possible. At this stage, large deflection, large end slip, and large major cracking of the concrete under line load were observed.

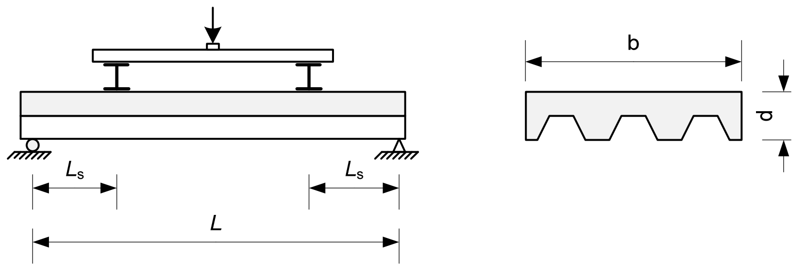

Figure 4: Bending test set up (Eurocode, 2004)

3. Test results and discussion

The loads presented in the discussion below refer to 'equivalent uniform load'. The equivalent uniform load was calculated by equating the maximum moments in the test specimen to the maximum moment of a uniformly loaded simply supported specimen.

3.1. Failure mode

In general, the slabs deflected linearly with the loads at the beginning of loading. Flexural cracks then initiated below the line loads and also in the constant moment region. As the loads increased, new cracks developed while the existing ones below or near the line load enlarged. In all tests, horizontal shear failure was observed which was indicated by slipping of concrete portion along the shear span towards the end of the span.

Graphs of loads versus mid span deflection for the two groups of specimens, one without screws and the other, with shear screws are shown in Figure 5. For specimens without shear screws, namely C1, C3 and C2, the load-deflection curves behaved almost linearly prior to first end slip. After the end slip has initiated, the load dropped drastically with a major crack occurred in the concrete below the line load. Failure in this manner is classified as brittle. Such failure is principally due to the large slippage between the steel sheeting and the concrete and is known as shear bond failure. For the specimens with screws, namely S1, S3 and S3, the load-deflection curves indicate that the loads dropped slightly when the first end slip had initiated, but it can be increased further and sustained for a longer period beyond the first end slip. The amount of deflection also has increased compared to the specimens without screws, which indicate that the failure can be delayed and the failure mode of the slab can be improved from brittle to ductile type by using shear screws.

3.2. Load bearing capacity and maximum deflection

Effect of slenderness

It can be seen from the load-deflection graphs shown in that the load capacity and the maximum deflection of composite slab specimens depend on the slenderness of the specimens. In general, the maximum loads increase when the slenderness decreases while the maximum deflection decreases with the slenderness.

The load bearing capacity of composite slab with and without shear screws increases exponentially when the slenderness decreases. This is shown by the graphs in Figure 6. Table 3 shows the values of average maximum loads, which increase as much as 3.5 times for the specimens without shear screws and 2.2 times for the ones with the shear screws, when the slenderness decreases from 10.0 to 4.8.

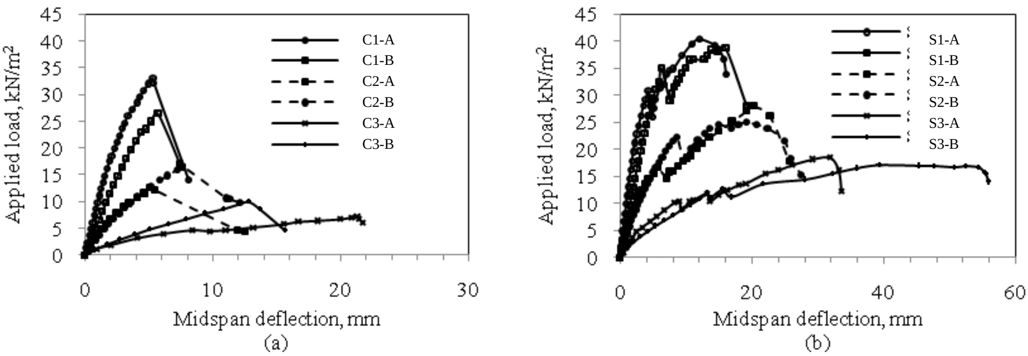

Figure 5: Load-deflection for specimens (a) without shear screws and (b) with shear screws

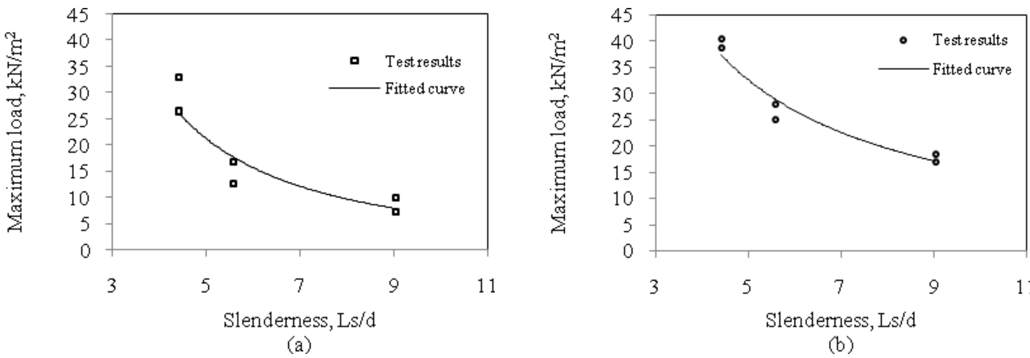

Figure 6: Maximum load versus slenderness for specimens (a) without shear screws and (b) with shear screws

Figure 7 depicts the relationship between the deflections at maximum loads and the slenderness. The graphs show that the deflection increases, also in exponent pattern, when the slenderness increases. As shown in Table 3, the average maximum deflections for both slabs with and without shear screws increase three times when the slenderness increases from 4.8 to 10.0.

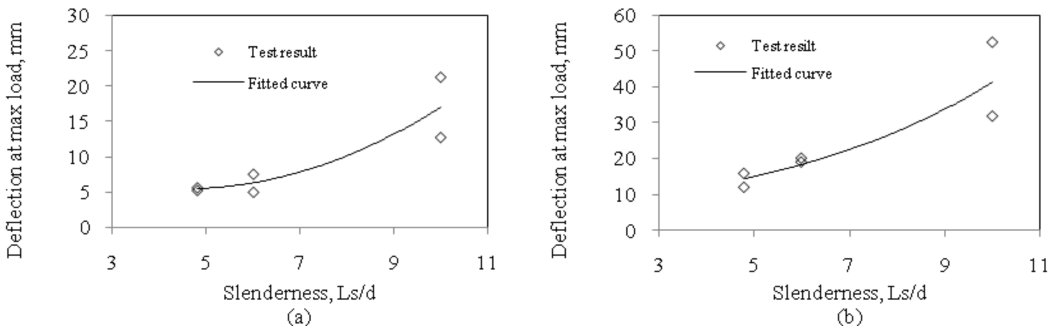

Figure 7: Deflection at maximum load versus slenderness for specimens (a) without shear screws and (b) with shear screws

Table 3: Average values of maximum loads and deflections

Specimen	Slenderness, L_s/d_p	Average W_{max}, (kN/m^2)	Amount of load increment	Average deflection, δ (mm)	Amount of displacement increment
C1	4.8	29.9	3.5	5.5	1.0
C2	6.0	14.7	1.7	6.4	1.2
C3	10.0	8.6	1.0	17.0	3.1
S1	4.8	39.7	2.2	14.0	1.0
S2	6.0	26.6	1.5	19.7	1.4
S3	10.0	17.7	1.0	42.1	3.0

Table 4: Comparison of maximum load and maximum deflection between specimens with and without shear screws

Specimen without shear screws	Average W_{max-c}, (kN/m^2)	Average δ_{max-c}, (mm)	Specimen with shear screws	Average W_{max-s}, (kN/m^2)	Average δ_{max-s}, (mm)	$\frac{W_{\max-s}}{W_{\max-c}}$	$\frac{\delta_{\max-s}}{\delta_{\max-c}}$
C1	29.9	5.5	S1	39.7	14.0	1.3	2.5
C2	14.7	6.4	S2	26.6	19.7	1.8	3.1
C3	8.6	17.0	S3	17.7	42.1	2.1	2.5

Effect of shear screws

The effect of shear screws on the maximum load and maximum deflection of the slabs can be determined by comparing the results for the specimens with the same slenderness. The load-deflection graphs as shown in Figure 8 clearly depict the improvement of the performance of the slab specimens when the shear screws are present. Values in

Table 4 show that the maximum loads for the specimens with shear screws had increased by 33%, 81% and 110% for specimens with the slenderness of 4.8, 6.0 and 10.0 respectively. The maximum deflection of the same specimens had increased by 150%, 210% and 150%. The results clearly indicate that the load bearing capacity can be increased and the mode of failure can be improved to a more ductile type by using shear screws. In addition, the effect of shear screws is more significant in slender slabs than in compact slabs.

The slab stiffness can be qualitatively expressed by the slope of the load-deflection graphs. It is clear from the graphs in Figure 8 that while the maximum load and deflection had increased by the presence of shear screws, the slope of the graphs in elastic range for both types of specimens are equal. This indicates that the stiffness of the specimen was not affected by the shear screws.

Safety factor

Deflection is the governing criteria for serviceability limit state of a structure. For a slab or beam supporting brittle materials, the deflection of the structures is usually limited to $L/360$. In this study, the maximum loads were compared with the load at deflection limit of $L/360$ to obtain safety factor for the slab at the deflection limit. The values as listed in Table 5 show that the safety factors are in the range of 1.2 to 1.6 for specimen without shear screws and from 1.2 to 2.0 for ones with shear screws. Again, the safety factor can also be increased by the presence of shear screws.

Horizontal shear bond stress

Force equilibrium method introduced by Abdullah and Easterling (2007) was used to estimate the horizontal shear stress at the concrete-steel interface from the bending test. The results are plotted against the measured end slips and presented in Figure 9. The average maximum horizontal shear stresses, τ for specimens C1 and S1 are 0.27 N/mm^2 and 0.32 N/mm^2; for specimens C2 and S2 are 0.15 N/mm^2 and 0.29 N/mm^2; and for specimens C3 and S3 are 0.13 N/mm^2 and 0.29 N/mm^2 respectively. The values indicate that the inclusion of shear screws had increased the horizontal shear capacities by 19%, 93%, and 123%. Again, the results also prove that the effect of shear connectors is more significant in the slender slabs.

Table 5: Safety factors at deflection limit of L/360

Specimen	Test	W_s at $L/360$ (kN/m^2)	W_{max} (kN/m^2)	$SF = \dfrac{W_{max}}{W_s}$	Average SF
C1	A	25.7	33.3	1.30	1.2
	B	23.3	26.5	1.14	
C2	A	9.2	12.7	1.38	1.2
	B	16.1	16.7	1.04	
C3	A	6.9	7.2	1.04	1.6
	B	4.6	10.0	2.17	
S1	A	31.8	40.5	1.27	1.2
	B	35.0	38.9	1.11	
S2	A	16.0	28.0	1.75	1.5
	B	21.8	25.1	1.15	
S3	A	9.9	18.5	1.87	2.0
	B	7.8	16.9	2.17	

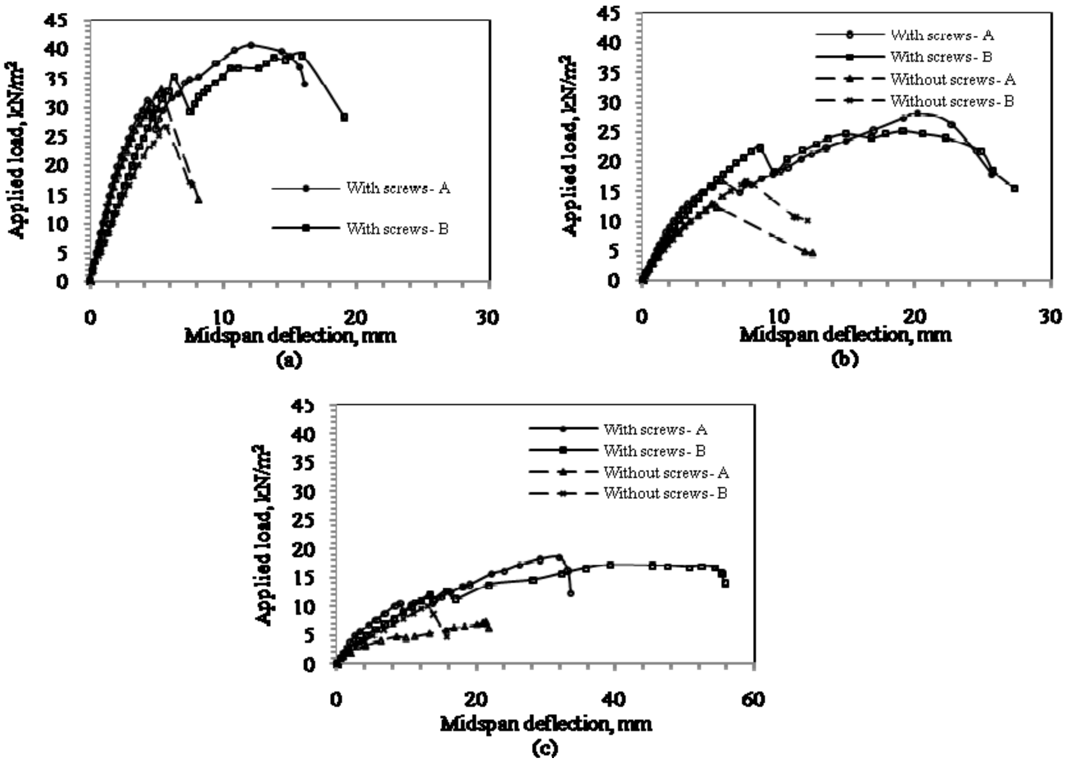

Figure 8: Load-deflection graphs depicting the effect of shear screws (a) C1 and S1, (b) C2 and S2 and (c) C3 and S3

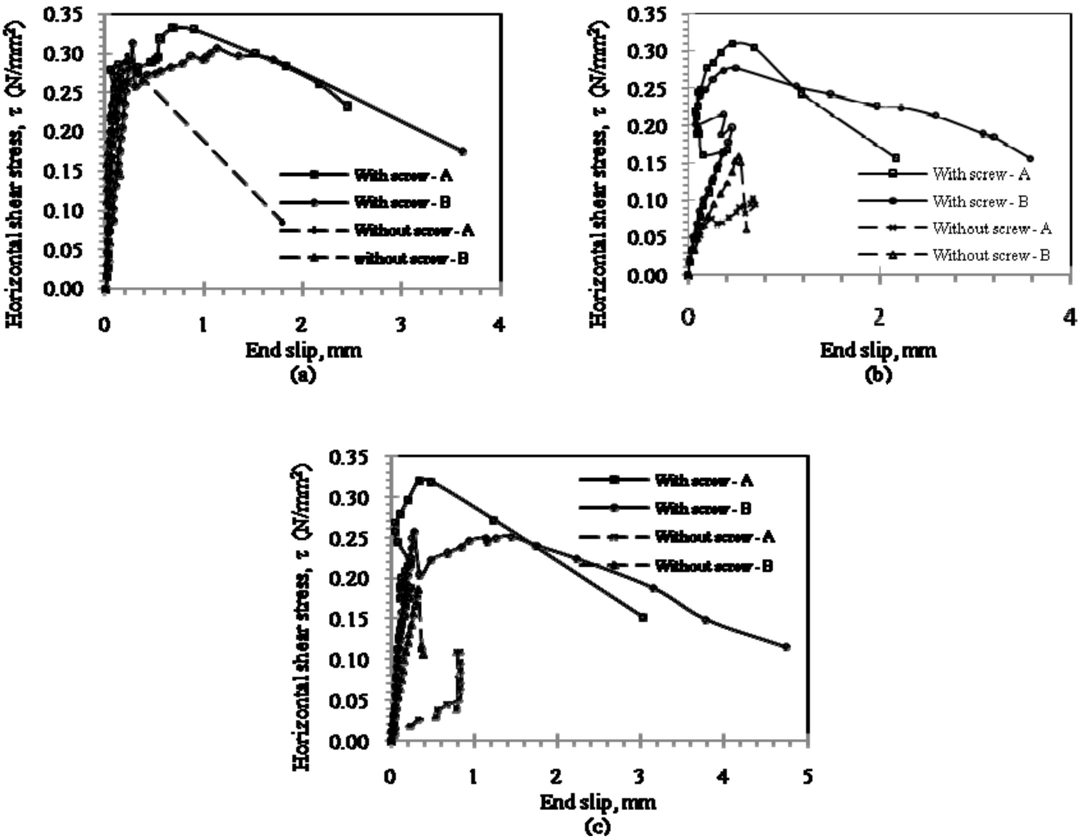

Figure 9: Horizontal shear stress-end slip plot for specimens (a) C1 and S1, (b) C2 and S2 and (c) C3 and S3

4. Summary and conclusions

Experimental study has been carried out to investigate the behaviour and load carrying capacity of steel deck-concrete composite slabs enhanced with shear screws at the steel-concrete interface. Twelve specimens of composite slabs with and without shear screws and with three different slenderness were subjected to two-point load bending test. From this experimental investigation, the conclusions can be deduced as follows:

i. The failure mode of composite slab can be improved from brittle to ductile, the load carrying capacity and the horizontal shear strength can be increased by installing shear screws at the steel-concrete interface.

ii. The shear screws has improved the safety factor for the slender slab but not as much for compact slab
iii. The effect of shear screws to enhance the performance of the slab is more significant in slender slabs than in compact slabs.
iv. The stiffness of composite slab below cracking limit does not change by the presence of shear screws.
v. The load carrying capacity of composite slab increases when the slenderness decreases and the maximum deflection increases when the slenderness increases. The increment of load carrying capacity and deflection is in exponential pattern. This relation is true for both slabs with and without shear screws.

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