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Longitudinal shear in composite deck slabs using corrugated steel sheets

Key words: corrugated sheets, shear transfer, shear span, slip, deflection

Introduction

Composite deck slabs can be defined as that slabs in which a profiled deck sheets are used as a base on which reinforced concrete is poured to make composite action. This composite phenomenon mentioned can be between this mass (corrugated sheets and concrete) and the supported steel beams through the use of shear connectors. A cold-formed steel deck sections are not only used as supporting form (mold) before hardening of concrete but also as a principal tensile reinforcement for the bottom fibers of the composite slab. Porter and Ekberg (1975) carried out full-scale tests on composite slabs to establish shear-bond failure mechanism. The steps of construction of such slabs can be seen in Figures 1 and 2.

The composite action is achieved by means of positive interlocking between corrugated steel sheets (deck) and the concrete by may be embossments, indentations, transverse wires attached to the deck corrugations, holes in corrugations or interface bonding between deck and steel.

Two types of steel sheets were used in trapezoidal and re-entrant shapes in bending and pushed out tests to find *m–k* parameters. The loads were applied longitudinally and transversely. That work was done by Wright et al. (1987). They concluded that increase in height of embossments will improve the load carrying capacity of the composite structure. A new method to determine the strength and stiffness of the composite slabs was developed by Easterling and Young (1992). A six slabs were cast and the

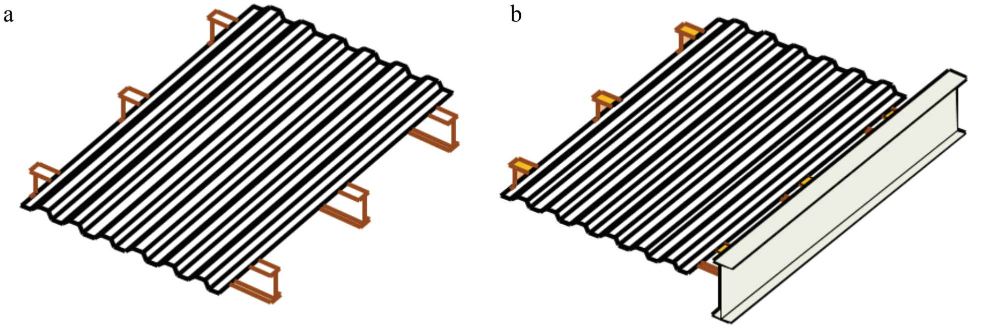

FIGURE 1. a – Steel beams supporting corrugated steel sheets; b – supporting beams rested on steel girders

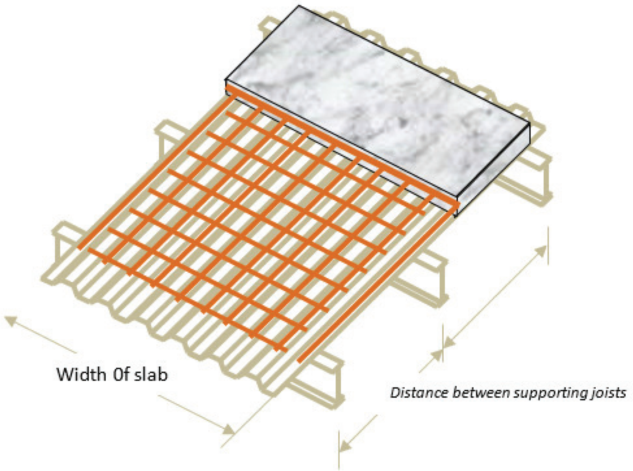

FIGURE 2. Erection of steel reinforcement and pouring of concrete

results of the analytical and experimental results were compared to reach the criteria in which a proper anchorage at the ends of the slabs should be provided.

Mäkeläinen and Sun (1999) studied the phenomena of shear connection in composite slabs using profiled steel sheets. A push-out tests were carried out on 27 samples. The parameters which were studied include different geometrical shapes, sizes, thickness of sheets and location of embossments. As a conclusion recorded was that the embossment depth plays a vital role in increasing shear stress. As a continuation of the previous work, Burnet and Oehlers (2001) developed a simulation of the bond between profiled sheets and concrete more accurate in push tests as a results of testing 33 specimens. Dove-tailed and trapezoidal rib shear connections were used to study chemical bond and mechanical bond strengths. A higher shear bond strength was governed in composite slabs that have end anchorage compared to that without end anchorage. That were the concluded remarks drawn by Chen (2003) in testing seven simply supported one span composite slabs.

Marčiukaitis, Jonaitis and Valivonis (2006) mentioned that the application of load on composite slabs using profiled steel sheets will lead to the truth that the connection between these sheets and concrete is not absolutely stiff and cracks shall appear in tension zone of the concrete. A new effort was recorded by Marimuthu et al. (2007) that the shear span is an effective parameter in composite slab uses embossed profiled steel sheets. If the shear span is short, the slab strength is governed by shear bond failure and by flexural failure in large shear spans. The partial interaction between the two materials of such composite structure was studied by Jeong (2008) making use of the push out tests. His work was coincided with the results governed from *m–k* method. The state of art recommends that this is a useful way to treat with partial interaction. The shear bond in composite slabs can be found from bending test data. This bond can be calculated through a procedure called force equilibrium method which is the effort produced by Abdullah and Easterling (2009).

Hedaoo, Gupta and Ronghe (2012) casted 18 full-scale composite slabs specimens to know their structural behaviour and load carrying capacity. He reached that the *m–k* method results are weaker than the experimental method by about 43%. One of the famous works to overcome slip in composite slabs was done by Lakshmikandhan, Sivakumar, Ravichandran and Jayachandran (2013) through using three types of mechanical connector schemes. During the tests of full-scale specimens, no any visible delamination and slip had been shown. The effect of thickness of the profiled steel sheets was studied by Cifuentes and Medina (2013) when three different thicknesses were tested. Thickness of these sheets show very important parameter in considering longitudinal shear strength especially in long-span specimens.

The effect of shear span was studied in Australia through testing four types of profiled decking, two of them trapezoidal and other two were re-entrant by Gholamhoseini, Gilbert, Bradford and Chang (2014). They studied two types of shear spans *L*/6 and *L*/4. The ultimate shear stress for *L*/6 is greater than that for *L*/4. Japan and Vakil (2014) studied theoretically the effect of varying profiled thickness with and without embossments by modeling that in ANSYS-15. The deflection and stress of the composite slabs were affected directly by thickness variation. The relation was found to be linearly proportional to some extent.

Experimental work

The experimental investigation of composite profiled slabs comprises the following activities:
- materials used;
- casting of slabs;
- testing of slab specimens and instrumentation.

The materials, which were used to prepare concrete, were confirmed with Iraqi specifications including cement, i.e. IQS 5/1984 standard (Central Organization for Standardization and Quality Control [COSQC], 1984b), gravel and sand, i.e. IQS 45/1984 standard (COSQC, 1984a). The mix design for concrete compressive strength was done in the lab to get concrete of 25 MPa. Steel reinforcement used were mesh fabric of 6 mm diameter bars and 150 mm C/C distance in two directions. The yield stress of the steel was 410 MPa. The steel sheets used were galvanized and their properties are listed in Table 1 and a part of the corrugation can be seen in Figure 3. These sheets are without embossments.

The slabs were casted after pouring the concrete on the steel sheets which will work as form before hardening of concrete. Concrete cubes, cylinders and prisms were taken to test them until the actual compressive and tensile strengths of concrete were governed. The profile steel sheets used has dimensions of 2.5 × 0.9 m. Wooden form was used to keep concrete in its position at the above boundaries of the slab. A mesh of 6 mm diameter bars at 150 mm C/C in both directions was used and suited at 25 mm above top of profile sheet.

The instrumentation was arranged and set up as shown in Figure 4 to test the hardened slab in accordance with the Eurocode 4. Part 1-1 (European Committee for Standardization [CEN], 2004). Linear variable differential transformers (LVDTs) were used to measure the horizontal slip as shown in Figure 4. They were installed in such a manner that two of them were used to measure slab slip and another two for measuring slip in profiled sheet to find out the relative slip between the concrete and the used corrugated steel sheet. A two dial gauges were fixed at the lower part of the mid--span length to read the mid deflection of the slab. The load was applied gradually through two-line loads across the transverse dimension of the slab at a rate of 1 kN in a start of the test. Afterwards it

TABLE 1. Properties of corrugated sheet

Property	Value
Width of corrugated sheet	0.9 m
Length of corrugated sheet	2.5 m
Thickness of the sheet	0.7 mm
Weight of the sheet	14.37 kg
Number of pieces in 0.9 m width of sheet	4.615
Length of each piece	215 mm
Total length in 0.9 m width of corrugated plate	992.23 mm
Gross area	694.56 mm^2
Distance from center of gravity to the base "y"	6.57 mm
Moment of inertia (*I*) about the centroidal axis	46 608 mm^4
Z_U (for upper position)	2 529 mm^3
Z_L (for lower position)	7 094 mm^3
Shear capacity of the profile sheet	25.25 $kN \cdot m^{-1}$
Moment capacity of the profile sheet	2.4 kN·m
Yield stress of the sheet (use coupons samples)	215 $N \cdot mm^{-2}$

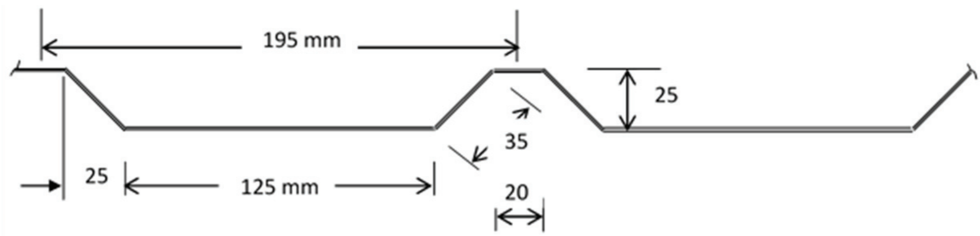

FIGURE 3. Profiled corrugated steel sheets

FIGURE 4. Test set up of the composite slab and casting concrete

is increased to 2 kN in a way that was shown in Figure 5.

The shear span is taken in a way that verified the provisions of the Euro-code 4. Part 1-1. It was taken in two ways short and long shear spans. The shorter shear spans must not be less than three times the composite deck depth

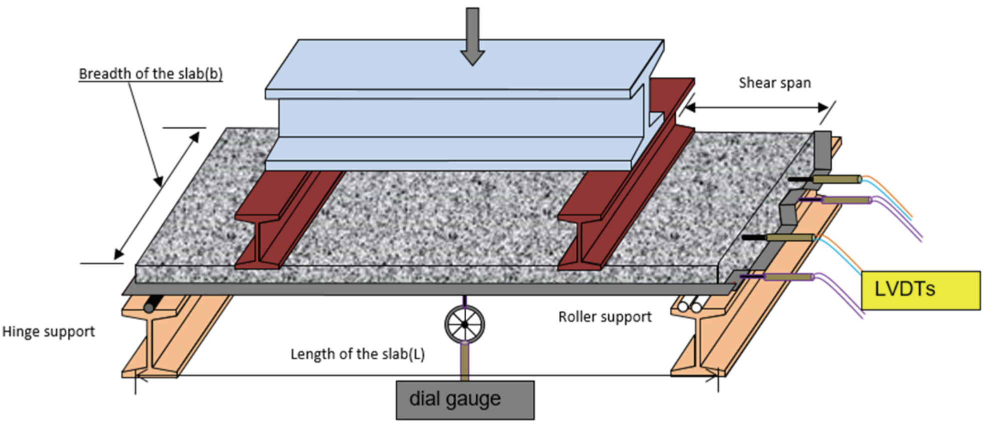

FIGURE 5. Arrangement of the slab test

and not more than 1,250 mm therefore they were taken as 600, 500 and 400 mm respectively in this study. The provision of the longer shear span is not less than 1/4 the slab length. So, they were selected as 800, 750 and 700 mm. According to Eurocode 4. Part 1-1, Clause 9.2.1, the following conditions were fulfilled:

1. The overall depth of the composite slab (h) shall be not less than 80 mm. The thickness of concrete (h_c) above the main flat surface of the top of the ribs of the sheeting shall be not less than 40 mm.
2. Transverse and longitudinal reinforcement shall be provided within the depth of the concrete (h_c).
3. The amount of reinforcement in both directions should be not less than 80 $mm^2 \cdot m^{-1}$.
4. The spacing of the reinforcement bars should not exceed $2h$ and 350 mm, whichever is the lesser.

For each shear span a static testing was done by applying loading till a mid--span deflection is reached a limit of 1/50 times span length. Cyclic testing was not done because most of literature studies recommended that it has no effect in shear transfer study.

Results and discussion

The results which were recorded include testing the slabs to find out the mid-span deflection and the longitudinal slip to build the equation mentioned by Porter and Ekberg (1975), through the investigation of finding m and k. This needs the results of testing three shorter shear spans besides three longer shear spans. The results of mid-span deflection of the shorter shear spans can be shown in Figure 6. As shown from the graphs they are taking same trend and deflections recorded are so small in the first stage in which higher values of loads are applied. As slip occurs the deflection is increased rapidly due to the appearance of shear cracks and separation of corrugated sheets from the concrete. This is really a new stage because a fluctuation is seen in the load applied. Afterwards a flexural crack had been started in the middle part of the slab till failure as shown in Figure 7. The appearance of these cracks facilitates the deflection to be increased. As shear span value increased, a higher deflection is registered and that is clear in results of 800 mm shear span in which the deflection was 60 mm compared to other shear spans.The maximum load was recorded in the minimum shear span (700 mm) where it was 21 kN and that is because the shear span is the arm of the applied load affecting on the nearest support. The same graphs trend was seen in testing and drawing the load deflection curves of shorter spans as seen in Figure 8 except that the values recorded of the loads and deflections are higher compared to the longer shear spans. This fact due to decreasing in the force arm and the delay in slip between sheets and concrete.

Figure 9 shows the relationships between load applied and slip for longer shear spans. The shape of these relationships like that of the deflection relations. The most important phenomenon seen in these relations including the shorter shear spans shown in Figure 10 that, very small values of slip are recorded at the start of the test while the loads reach higher values near or equal to ultimate or

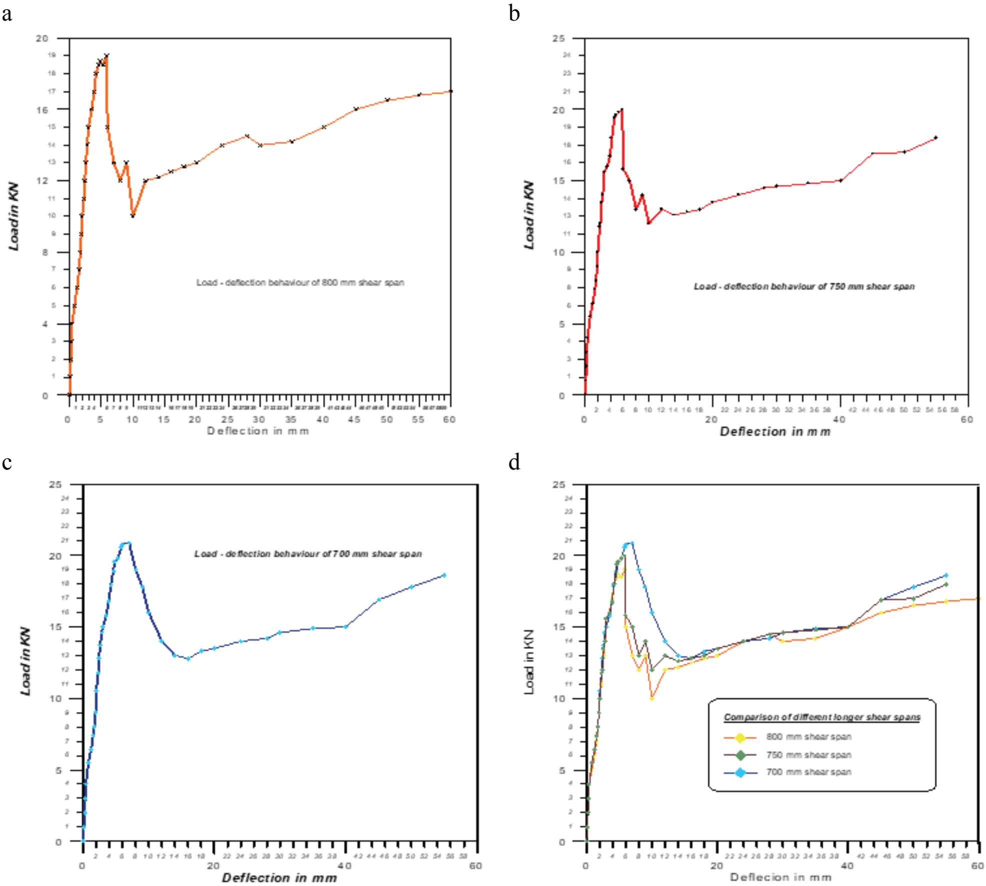

FIGURE 6. Mid-span deflections of shear spans: a – 800 mm; b – 750 mm; c – 700 mm; d – comparison among the three shear spans

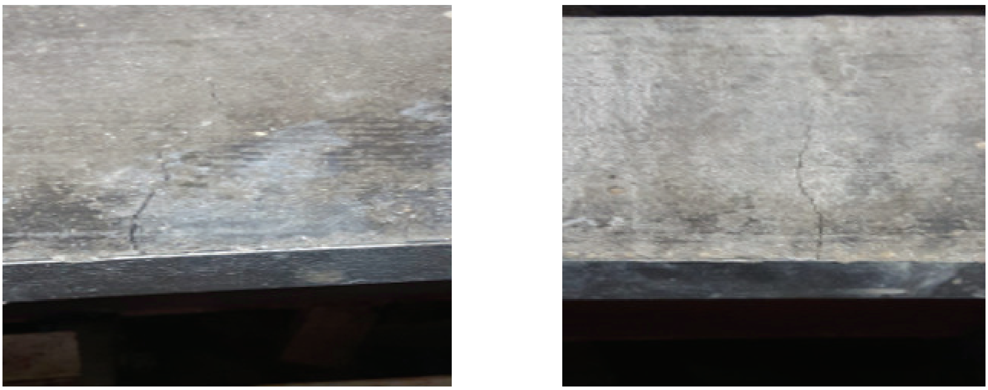

FIGURE 7. Shear and flexural cracks appeared during tests of the composite slabs

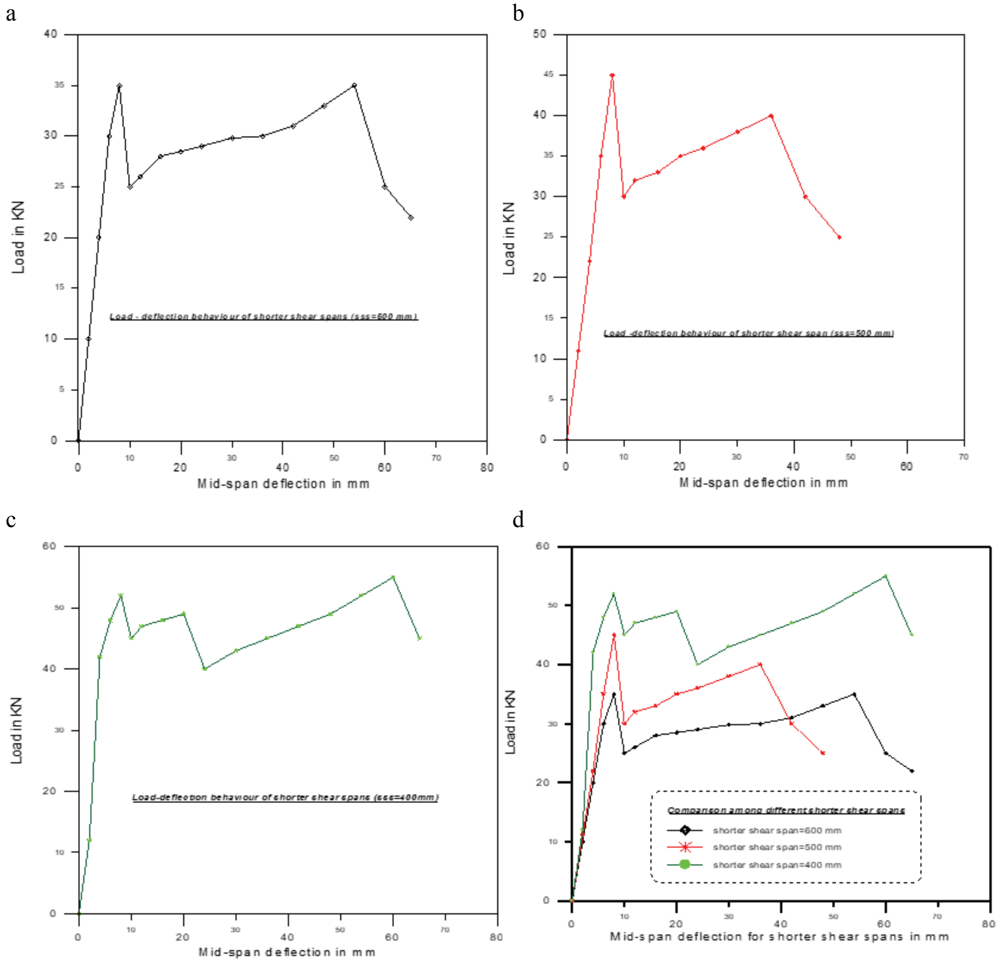

FIGURE 8. Mid-span deflections of shear spans: a – 600 mm; b – 500 mm; c – 400 mm; d – comparison among the three shear spans

failure load. The explanation of this matter is that as load increased deflection in the middle region of the slab increased. This condition try to break the bonds between the concrete and sheets at the end edges of the slab and ignores the monolithic action therefore slip increased as deflection increased and that is clear from whole curves. In the two types of spans the slab material behaves as brittle under the applied load and as deflection and slip increased it will behave as ductile as it was shown in all relations that all failure loads are less than the maximum load registered at very small slips.

In Eurocode 4. Part 1-1, Clause 9.7.3, Point 3 states that "the longitudinal shear behaviour may be considered as ductile if the failure load exceeds the load causing a recorded end slip of 0.1 mm by

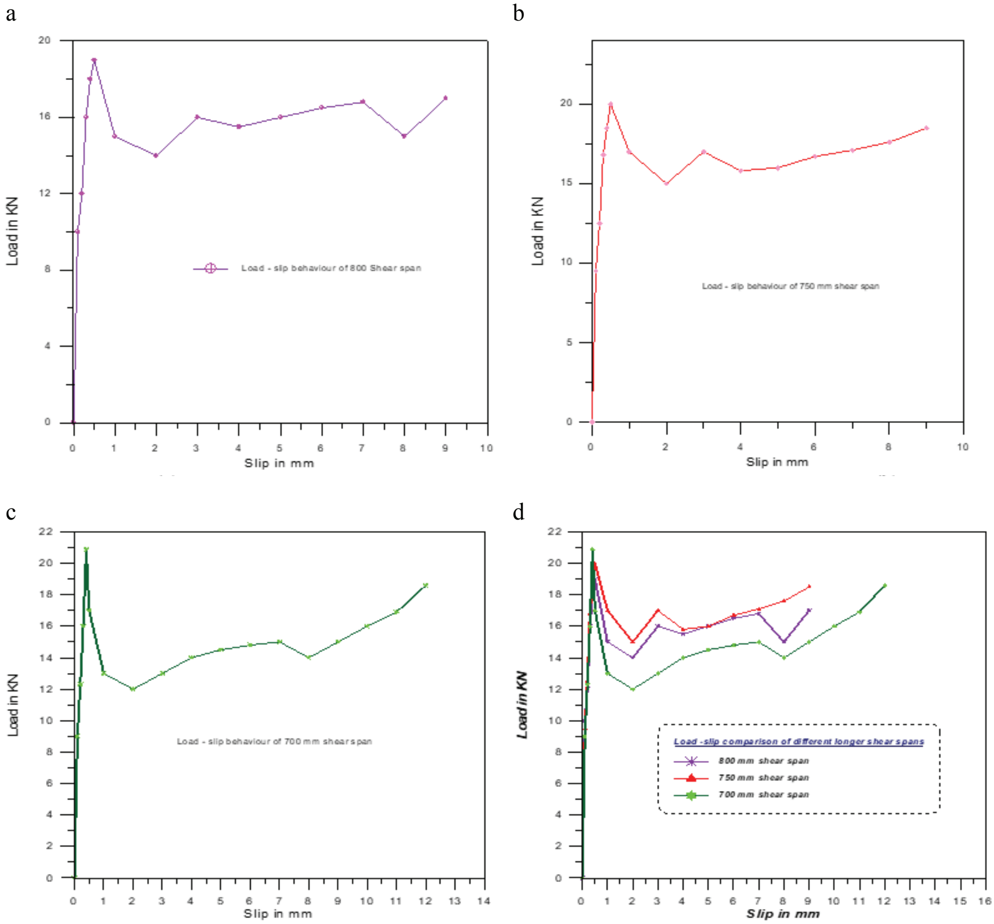

FIGURE 9. Slip of shear spans: a – 800 mm; b – 750 mm; c – 700 mm; d – comparison among the three shear spans

more than 10%. If the maximum load is reached at a midspan deflection exceeding $L/50$, the failure load should be taken as the load at the midspan deflection of $L/50$" (CEN, 2004, p. 102). The results of the present study are coincided with this clause for shorter and longer shear spans. Point 4 in the same clause recommended the equation of the design for shear bond capacity of composite deck slabs as:

$$\frac{V_u}{bd_p} = m\frac{A_p}{bL_s} + k \qquad (1)$$

So, this equation is a linear equation in which the slope of the straight-line m must be determined and the intercept k also to evaluate the shear transferring capacity of the profiled sheet. The evaluation of these two parameters needs an

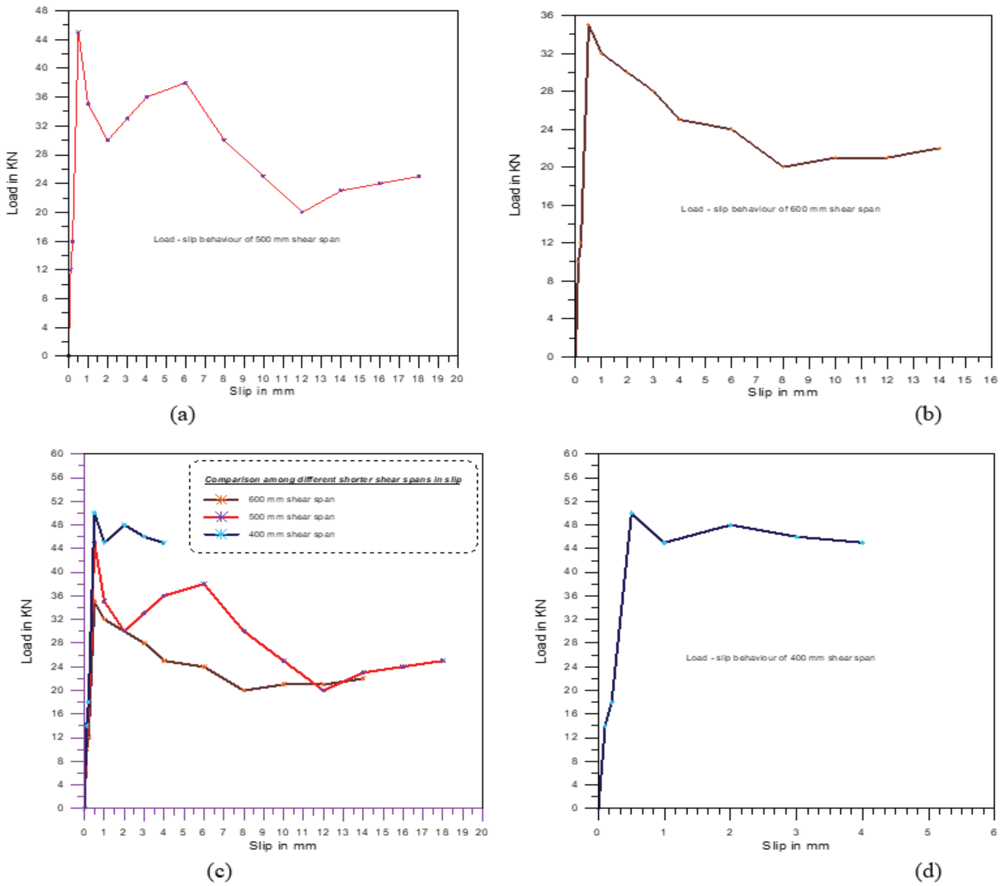

FIGURE 10. Slip of shear spans: a – 600 mm; b – 500 mm; c – 400 mm; d – comparison among the three shear spans

experimental test for each new type of profiled steel sheets and that is the main aim of the present study. In drawing the results of the shorter and longer shear spans where V_t is taken to be 0.5 the failure load including the own weight of the slab and corrugated sheet, the straight line will be governed as shown in Figure 11. The slope of this line represents m and k is represented by the intercept. The values of these parameters determined from this study are m = 65 and k = 0.094.

The design equation for this corrugated steel sheets will be:

$$\frac{V_u}{bd_p} = 65 \cdot \frac{A_p}{bL_s} + 0.094 \tag{2}$$

To make comparison with other profiled sheets, the values evaluated for this new corrugated sheet can be seen in Table 2.

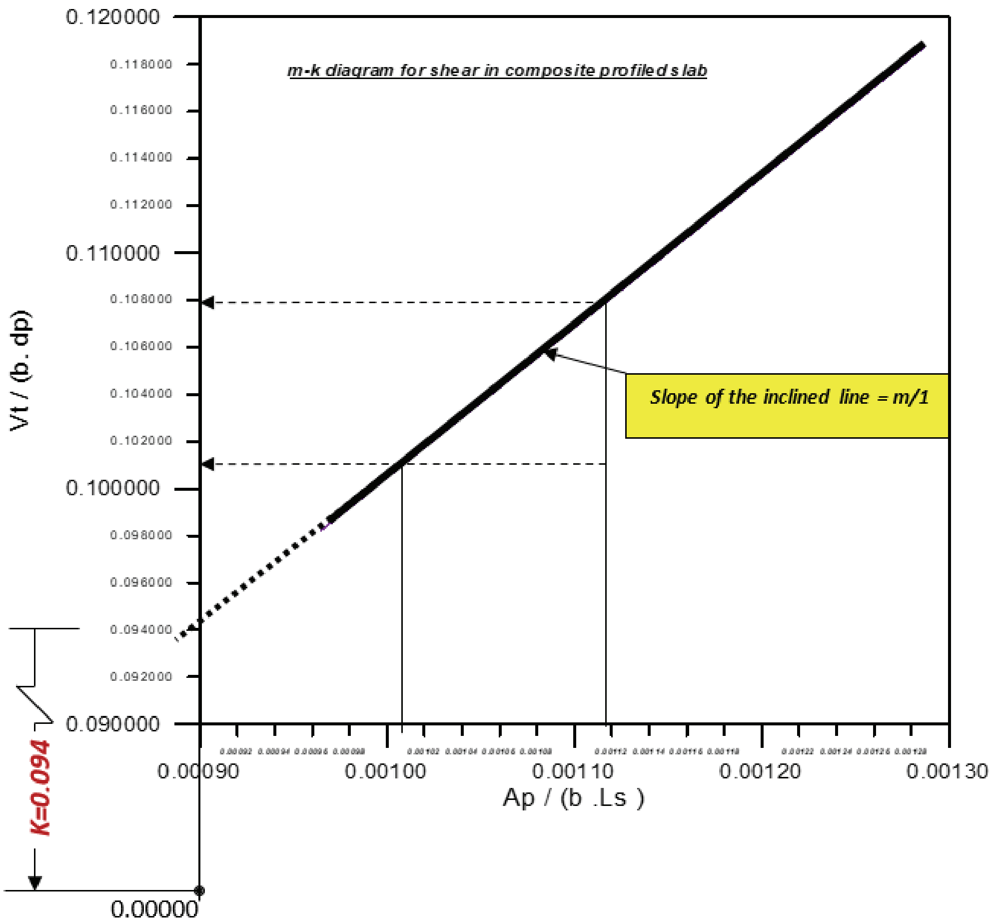

FIGURE 11. Graph of *m*–*k*

TABLE 2. Comparison among available profile steel sheets

Reference or author	Profile type	Embossment type	*m*	*k*
Wright, Evans & Harding (1987)	trapezoidal	Chevron embossments @90°	107.527*	0.0401
Chen (2003)	trapezoidal	Chevron embossments @0°	84.665*	0.0221
Marimuthu et al. (2007)	trapezoidal	rectangular dishing type of embossments	87.956*	0.0322
Saravanan, Marimuthu, Prabha, Arul Jayachandran & Datta (2012)	trapezoidal	rectangular embossments in web and flange	96.95*	0.043
Present work	trapezoidal	without embossments	65	0.094

*Saravanan et al. (2012).

Conclusions

As a result of the use of different longer and shorter shear spans to investigate the effect of using this type of profiled steel sheets, the following conclusions can be mentioned:

- The value of *m* is the predominant factor in the shear design transfer equation, therefore increasing it means increasing the value of shear transferred and yet slip will occur. In the present study the value of *m* is the smallest among others while *k* is the largest value recorded. The evaluated values of *m* and *k* are 65 and 0.094 respectively.
- The present type of sheets is used here in wide range, therefore need to study shear transfer becomes a pressurized matter. A recommendation here can be drawn that if a shear connector can be added to the action of using such sheets in composite slabs.
- All samples tested pass through two stages brittle and ductile. No sample failed in sudden or catastrophic failure.

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Summary

Longitudinal shear in composite deck slabs using corrugated steel sheets. Profile deck steel sheets are used in composite deck slabs. These sheets are standard in dimensions and shapes besides they are supplied with embossments and indentations. Such sheets are not available in Iraqi markets nowadays therefore people used another type of sheets which are corrugated without embossments or indentations in very wide range. This study covers the use of such sheets in composite slabs as decks instead of standard profiled steel sheets. The study comprises testing slabs of dimensions 0.9 × 2.5 m reinforced by steel fabric mesh and rested on corrugated sheets. Two types of shear spans are selected shorter and longer to study the longitudinal shear force transmitted due to the applied loads according to the Eurocode 4. The shorter shear spans are 600, 500 and 400 mm while longer one is 800, 750 and 700 mm. The study extended to support the requirements of design equation of the Eurocode by shear bond method also known as *m–k* method. The evaluated values of *m* and *k* are 0.094 and 65 respectively. The result of *k* which plays a very important role in shear transfer is small compared to what available in literature, therefore it is recommended to make use of shear connectors in such construction or any else method.

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