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Experimental investigations on composite slabs to evaluate longitudinal shear strength

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Abstract. Cold-formed steel profile sheets acting as decks have been popularly used in composite slab systems in steel structural works, since it acts as a working platform as well as formwork for concreting during construction stage and also as tension reinforcement for the concrete slab during service. In developing countries like India, this system of flooring is being increasingly used due to the innate advantage of these systems. Three modes of failure have been identified in composite slab such as flexural, vertical shear and longitudinal shear failure. Longitudinal shear failure is the one which is difficult to predict theoretically and therefore experimental methods suggested by Eurocode 4 (EC 4) of four point bending test is in practice throughout world. This paper presents such an experimental investigation on embossed profile sheet acting as a composite deck where in the longitudinal shear bond characteristics values are evaluated. Two stages, brittle and ductile phases were observed during the tests. The cyclic load appears to less effect on the ultimate shear strength of the composite slab.

Keywords: composite slab; embossed profile sheet; *m*-*k* value; longitudinal shear strength.

1. Introduction

Now-a-days steel concrete composite profile deck slab are widely used as flooring system in the construction industry since they increase the speed of construction. It consist of cold formed profile sheets of thickness varying from 0.6 mm to 2.5 mm, concrete blocks of nominal thickness ranging from 50 mm and nominal shrinkage reinforcements. A composite slab is defined by ASCE (1992) as “a slab system comprising normal weight or light weight structural concrete placed permanently over cold formed steel decks in which the steel deck performs dual roles of acting as a form for the concrete during construction and as positive reinforcement for the slab during service”. This floor system has many advantageous over conventional floor system such as acting as safe working platform, formwork for concrete, by acting as tensile reinforcement, reducing laborious work of fixing of reinforcements, reducing the dead weight of slabs significantly by shape of the profile sheets, increases the headroom by allowing the service ducts within the depth of the slab and significant reduction of construction time. However, it has some disadvantages that when exposed to atmosphere the resistance to fire is comparably low, needs laborious work for the prediction of shear bond characteristic and this type of

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flooring is not recommended for a structure subjected to heavy concentrated loads.

In general, three mode of failure have been recognized from the investigations made on composite slab. The three modes of failures are (i) flexural mode (ii) vertical shear mode and (iii) longitudinal shear mode. Out of them, the longitudinal shear failure mode is a complex phenomenon. It is affected by many parameters such as type, size, shape, spacing and orientation of embossments, shape of profile sheets, thickness of profile sheets and concrete grade. Many investigations had been conducted on these parameters. Wright *et al.* (1987) reported that the variation in concrete strength and application of cyclic loading had little effect on the ultimate capacity of composite slab and also they had reported that the height of the embossment had a very significant effect upon the ultimate strength.

Makelainen and Sun (1999) studied the longitudinal shear behaviour of composite slabs by varying the parameters such as shapes, sizes, locations of embossments and sheeting thicknesses. All specimens failed in a brittle manner and no plastic deformation was observed. They also reported 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 sheet. Burnet *et al.* (2001) conducted thirty three tests to determine the main parameters that affect both the chemical bond and mechanical bond strengths of dovetailed and trapezoidal rib shear connectors. The main parameters are shape of rib shear connector, embossments, thickness and plate surface preparation of sheet. From this investigation, it is clear that the chemical bond mainly varies by geometry and it was more in dovetail shape than in trapezoidal shape and the effect of embossment in enhancing shear strength is significant in trapezoidal shape than in dovetail shape.

Since, a number of parameters are involved in longitudinal shear behaviour of composite slab; there are no numerical equations to find the longitudinal shear capacity of composite slabs. However, EC 4 suggests the full scale experimental investigations to find two constants '*m*' and '*k*' which can be used to determine the longitudinal shear capacity. Fig. 1 shows the experimental setup to evaluate the '*m*' and '*k*' values. By varying the shear span (L_s), the three failure modes can be achieved which is illustrated in Fig. 2. In which the flexural mode starts in the origin and when shear span falls between A to B the failure mode classified as longitudinal shear mode. Above that when the shear span is very short the failure mode is vertical shear. The shear span has to be selected in such a manner that the failure should occur in the region between A to B as in Fig. 2. According to the specification, atleast two groups of three tests should be performed. One group in a shorter shear span region and one in longer shear span region. In each group, one of the three tests should be subjected to static loading and

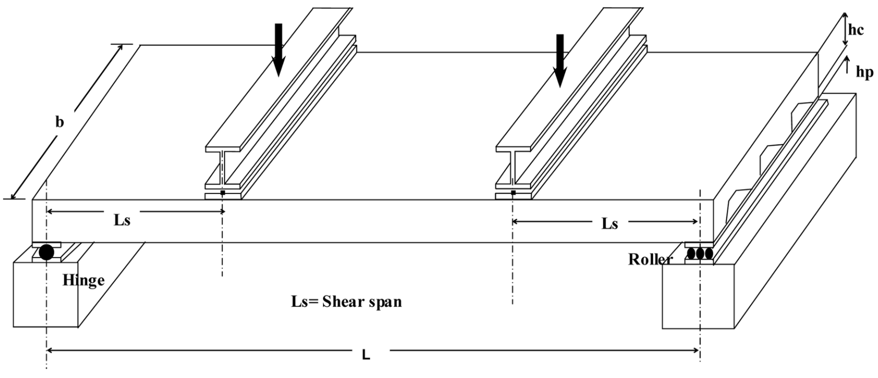


Fig. 1 Schematic view of the experimental set-up

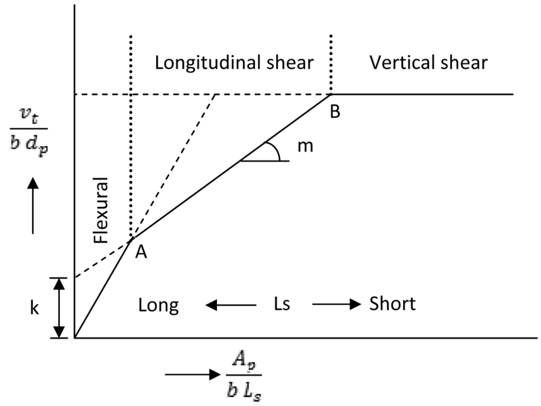


Fig. 2 Possible failure modes

remaining two should be subjected compressive cyclic loading followed by monotonic load till failure.

Expensive and complex nature of this experimental investigation suggested by EC 4 lead the researchers to develop some simple small scale pull out tests. Crisinel and Marimon (2002) proposed a new simplified 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. Emanuel Lopes and Rui Simoes (2008) compared the Eurocode 4 method with the new simplified method developed at Federal Polytechnic School of Lausanne (proposed by Crisinel *et al.*, 2002) based on the pull out tests with the goal of verifying the analytical formulation. They concluded that this method can be an alternative method; however, they suggested verifying the results with real cases. Burnet and Ohelers (2001) also studied various pull out test suggested by other researchers. With these studies, they proposed new form of push test.

Mostly small scale test were conducted to find the effect of various parameters that affects the behaviour of composite slab and to suggest the simplified method for finding the longitudinal shear capacity. Though several simplified methods are available to find longitudinal shear capacity, most of them have their own limitation because of various parameters involved and still no international codes suggests any simplified method. Hence it is almost become mandatory to conduct the m-k method for every new type of profile sheets. In this test, the cold formed steel profile sheet are used which has been designed using latest US technology to achieve blend of strength and economy. The details of the sheets are given in Appendix-I.

2. Experimental investigation

The experimental work is conducted with the aid of Eurocode 4. Based on Eurocode 4, for the reliable results, three shorter shear spans and three longer shear spans of simply supported specimens with two equal line loads placed symmetrically are chosen for the experimental work. According to this, 3 tests have to be conducted for each shear span (one monotonic test and two cyclic tests). Therefore, totally eighteen tests are conducted to evaluate shear bond characteristic for this particular

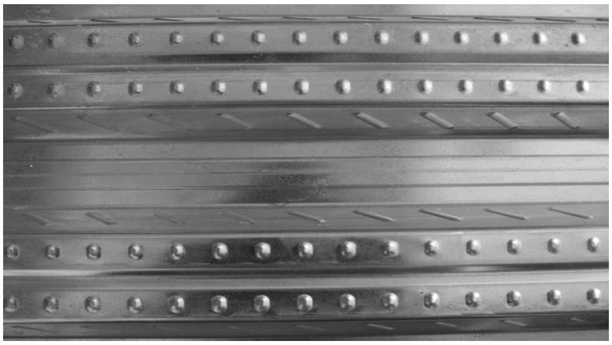


Fig. 3 Pictorial view of cold formed embossed sheet

type of profile acting as composite deck.

The cold formed steel sheet profile sheet are used in this test has been designed using latest US technology. The size of the single profile sheet used in these tests is 3.1 m × 0.9 m and the size, shape and frequency of embossments details of profile sheet are given in Appendix-I and shown in Fig. 3. A wooden mould is prepared to accommodate the profile sheet. The M20 grade of concrete is chosen and designed according to Indian code IS:10262 for casting the composite slab. 6 mm dia. of 250 mm c/c reinforcement mesh provided on both direction of the slab at 25 mm from top of the profile sheet to minimize the shrinkage of the concrete. The casting is carried out in a fully supported condition and the levels are checked before concreting. The tests are conducted after the 28th day of casting and the slabs are cured atleast for 14 days.

Fig. 4 shows the experimental setup. The experiments are conducted using 50Tonne servo controlled hydraulic actuator to apply the load by displacement control. The load is applied as shown in Fig. 4 as two equal line loads distributed across the width of the slab by transferring the actuator load through a distribution beam of I-sections. The deformations in the slab are measured using LVDTs and dial gauges. LVDT with the range of 100 mm is used to measure the mid-span deflection of composite deck as shown

Fig. 4 Experimental setup

Fig. 5 LVDT at the mid span of the slab

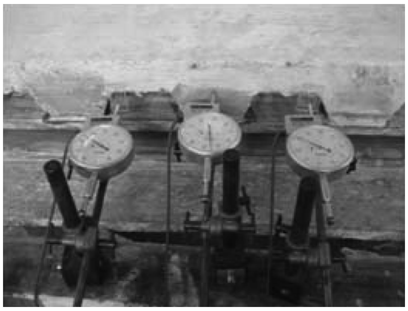


Fig. 6 Dial gauges to measure the end slip

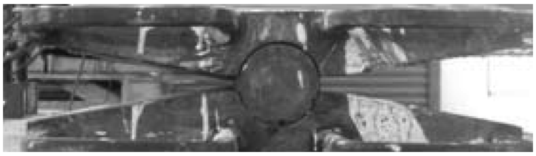


Fig. 7 Hinge Support used in experiment

in Fig. 5. To measure the relative slip between the profile sheet and concrete, the plastic sheets are pasted on steel in such a manner that the dial gauges can measure the deformation of steel as shown in Fig. 6. Three numbers of dial gauges with the range of 50 mm are used to measure the slip on the either side, one on concrete surface and two on steel profile sheets. The rollers and hinges are specially fabricated to support the composite slab. The roller support comprises of three rods placed side by side sandwiched by two plates. The hinged support used is as shown in Fig. 7. The data's are acquired through data logging system of MGC Plus which will store the data's automatically at required intervals.

The shear span is defined as the distance between the centre of supports at either end to the point of application of the line load in the slab as shown in Fig. 4. According to Eurocode 4, the shorter shear span should not be less than 3 times the depth of composite deck (309 mm) and not greater than 1.25 m. The shorter shear span should be less than and longer shear span should be greater than $1/4^{th}$ of the span of the slab in such a way that the flexural failure should not occur. Hence, the shorter shear spans of 350 mm, 400 mm and 450 mm and the longer shear spans of 850 mm, 950 mm and 1050 mm are selected in the present study.

For each shear spans, three tests have to be conducted, one under static loading for the duration of failure should not be less than one hour and two under cyclic loading of 5000 cycles for the duration of 3 hours in first phase and then monotonic loading has to apply until failure for the duration should not be less than one hour. In static testing, the loading is applied by deflection control with the rate of 0.25 mm/min and the frequency of data acquisition is 1 Hz. A maximum mid span deflection limit was set to shut down the actuator to avoid sudden collapse of the specimen. The test is terminated when the mid-span deflection is reached a limit of span/50.

In cyclic testing, the compressive cycles of loading have to be applied in the ranges between 0.5Wq to 1.5Wq, where Wq is the anticipated value of the characteristic load which will be acting on the slab. In this experimental investigation, Wq is taken as 3 kN/m^2 according to IS: 875 (Part-2)-1975 for commercial building. This uniformly distributed load was converted in to a concentrated total central load and applied in the range of 3.78~11.34 kN. Fig. 8 shows the loading pattern for cyclic loading.

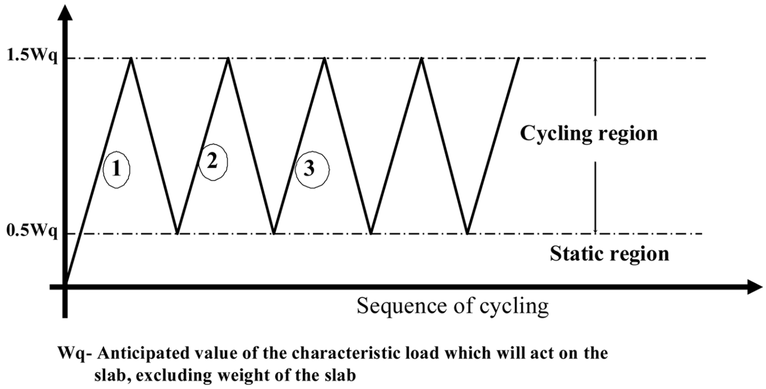


Fig. 8 shows the loading pattern for cyclic loading

This compressive cycle of loading is applied by load control with the rate of 0.46 cycles per second. For the data acquisition, the frequency of data storage is 10 Hz. After the completion of cyclic loading, a monotonic load is applied as explained in static test.

3. Results and discussion

3.1 Static test

Load deflection behavior for three shorter shear spans are shown in Fig. 9. It is observed that all the specimens exhibited the same trend of behaviour in two phases. In first phase, it can be seen that the initial stiffness of all the specimens are almost equal and then the failure load of the specimens decreases with increase in shear span. Once the failure load reaches sudden load drop is occurred with the sound of separation between the concrete and steel. At this time, near the loading point shear cracks are formed and the slip between steel and concrete is initiated as shown in Fig. 10.

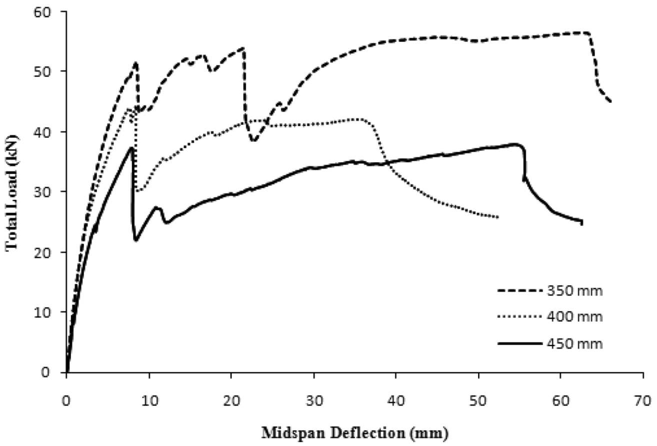


Fig. 9 Load-deflection behaviour of shorter shear span

Fig. 10 Crack formation

When the slip is started in first phase, the monolithic action between the sheeting and concrete is lost. Now, in the second phase, the concrete slab tries to ride over the embossments and increasing the load gradually. Flexural cracks are also starts developing towards the mid-span. Particularly in shorter shear span the ultimate load in the second phase is almost more or equal to failure load. The probable reason could be, after the longitudinal shear failure, higher moment is required to cause flexural failure. Fig. 11 shows the load-slip behaviour of shorter shear spans specimens. Load slip behaviour also follows the same trend as that of load deflection behaviour. There is no slip up to the failure load and slip is increased with increasing mid-span deflection. The amount of slip is less in 350 mm shear span because the slip is occurred at either end at the time of subsequent sudden load drop and maximum slip of 18 mm was observed in 400 mm shear span. Fig. 12 shows the relative movement between concrete and profiled sheet.

Load deflection behaviour and load slip behaviour of longer shear span are shown in Figs. 13 and 14. As in the shorter shear span, in longer shear span also have two stage of behaviour. The first stage is the portion up to first recorded slip and the later portion atleast up to 56 mm of mid-span deflection is called as second stage. In both stage, the behaviour of longer shear span is similar to shorter shear span. However, the longer shear span specimens attained the ultimate load at first stage itself but the shorter

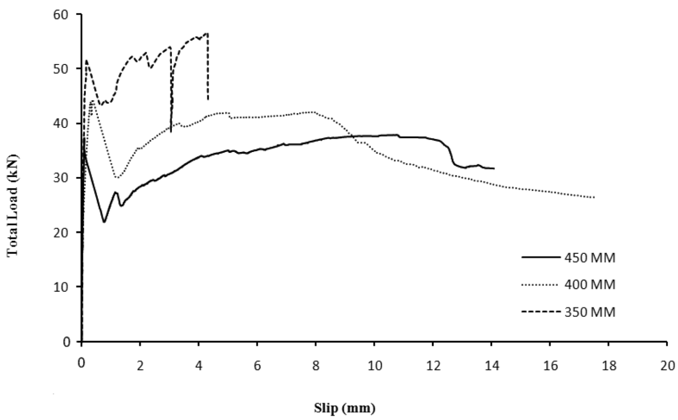


Fig. 11 Load-slip behaviour of shorter shear span

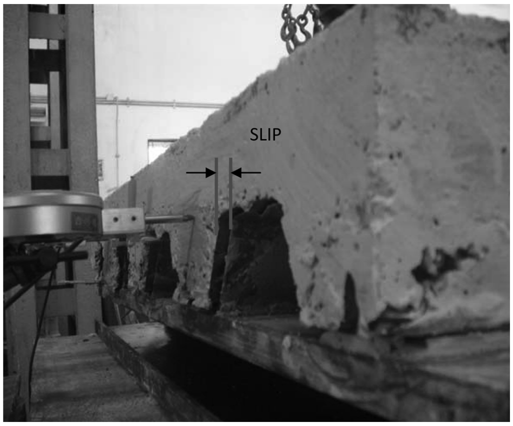


Fig. 12 Slip between concrete and steel sheet

shear span specimens attained the same in second stage. As expected, all the specimens failed in longitudinal shear mode by cracking at the point of loading with subsequent separation between concrete and cold formed steel profile sheet. The load slip behaviour and cracking pattern of longer shear span specimen also similar to the behaviour of shorter shear span. The average amount slip is observed in longer shear span is approximately 10 mm. As in 350 mm shear span, the subsequent load drop is observed in 1050 mm shear span with the initiation of end slip.

3.2 Cyclic test

Two cyclic tests have conducted for each shear span to remove the possible chemical bond between concrete and profile sheet. As mentioned in the experimental setup, the compressive cyclic loads of 5000 cycles in the range between 3.69 kN to 11.26 kN are applied for the duration of 3 hours. During the whole period of cyclic test no failure is observed in all the shear spans and also no slip is observed. In all the cases the small permanent strains are observed and in some case only the separating sounds are

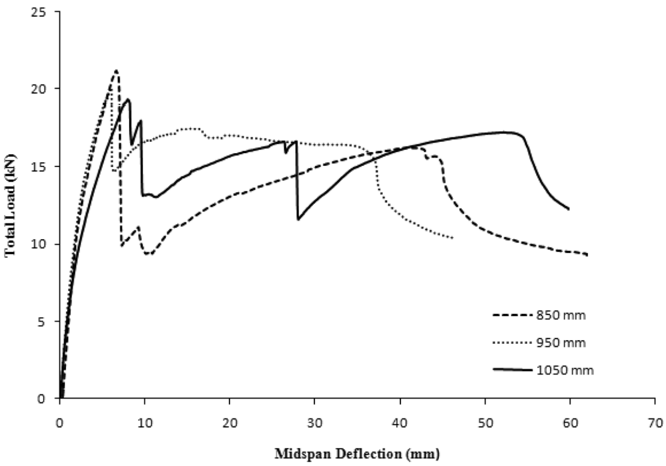


Fig. 13 Load-deflection behaviour of longer shear span

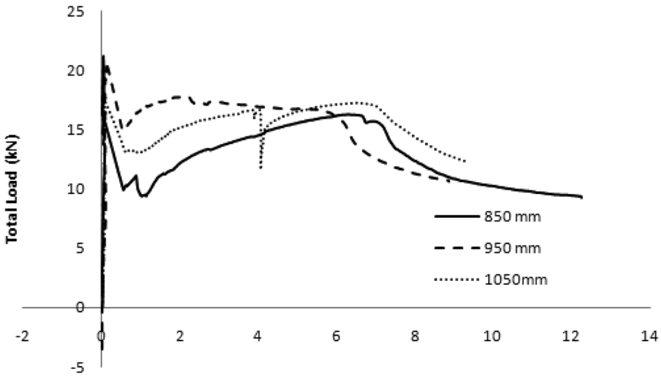


Fig. 14 Load-slip behaviour of longer shear span

observed. The trend of behaviour, in monotonic test after the completion of cyclic test, is similar to the static test in terms of load deflection behaviour and load slip behaviour of composite slab. There is no much effect on failure load of composite slab due to the cyclic loads as compared with static failure load.

3.3 Evaluation of m-k value

The main objective of the present testing programme is to determine the '*m*' and '*k*' values which define the shear transferring capacity of the profiled sheet. According to Eurocode 4, recommended design equation for shear bond capacity of composite deck slabs is given by

$$\frac{V_u}{bd_p} = m\frac{A_p}{bL_s} + k$$

which is in the form of an equation for a straight line $y = mx + c$.

From the experimental investigation, the behaviour of composite slab is classified as brittle behaviour. Hence, as per specification, a shear force is taken as 0.4 times of failure load, W_t. The failure load is calculated by adding self-weight of the slab and weight of the distribution beams to imposed load for each specimen. Average value of shear force for each shear span (average of one statically loaded and two cyclically Loaded for single shear span) is calculated to determine *m* and *k* values. Table 1 shows the calculation of necessary parameters for plotting the curve. A further reduction of 10% is applied to obtain the reduced regression line as shown in Fig. 15 based on which the values of the regression constants *m* and *k* are computed.

The values obtain from the present study are compared with other profiled sheets consist of chevron type embossments with 0º and 90º and rectangular dishing type embossment reported in literature (Table 2). It was inferred that each profiled sheet has its own unique properties.

4. Conclusions

From the investigations conducted on composite slab by varying shear spans, the following conclusions are derived:

Table 1 Parameters to plot m-k curve

No	L_s	V_t (kN)	$V_t/b.d_p$ (N/mm^2)	A_p/bL_s
1	350	22.56	0.32140	0.00284
2	400	20.43	0.29096	0.00249
3	450	18.63	0.26540	0.00221
4	850	11.19	0.15944	0.00117
5	950	10.49	0.14937	0.00105
6	1150	9.38	0.13367	0.00095

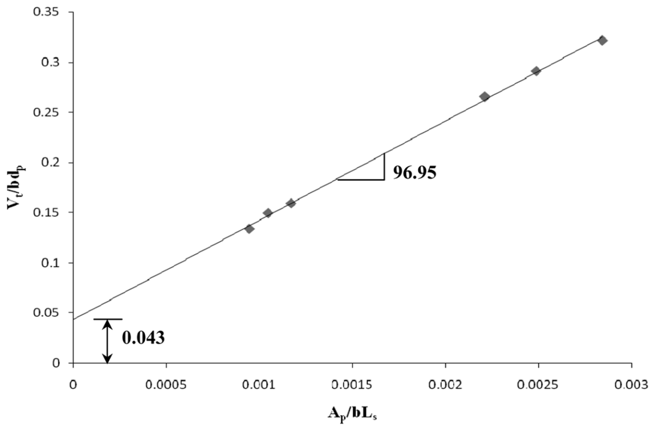
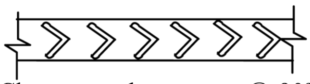
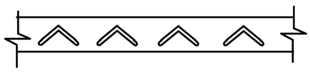
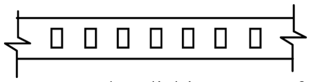
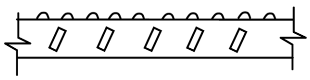


Fig. 15 *m-k* curve

Table 2 Comparison of different profile sheet

Author	Type of profile	Embossment type	*m*	*k*
H.D. Wright *et al.* (1987)	Trapezoidal	 Chevron embossments @ 90º	107.527	0.0401
S. Chen (2003)	Trapezoidal	 Chevron embossments @ 0º	84.665	0.0221
V. Marimuthu *et al.* (2007)	Trapezoidal	 Rectangular dishing type of embossments	87.956	0.0322
Present work	Trapezoidal	 Rectangular embossments in web and flange	96.95	0.043

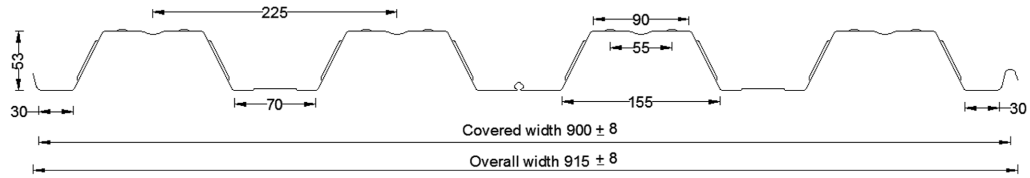


Fig. 16 Cross sectional details of embossed profile sheet

1. The *m* and *k* values are varying parameters depending upon many parameters involved in composite slab. Hence, every new configuration of cold formed steel profile sheet needs an experimental investigation for reliable design.
2. In all the specimens, two stage of behaviour is observed. First stage is brittle and second stage is ductile. This ductile behaviour can be utilized in collapse analysis. Also there is no catastrophic failure in all the specimens.
3. As reported in the literature, the cyclic loading has no much effect on the ultimate load capacity of composite slab. This aspect has been corroborated in the present tests.
4. The minimum limit of shorter shear span is 3 times the thickness of the slab as per specification. But the authors are of the opinion that this could be at least 4 times the thickness of the slab. So that we can get more realistic longitudinal shear behaviour of composite slab.
5. The linear regression constants '*m*' and '*k*' for rectangular type embossments are found to be: $m = 96.95$, $k = 0.043$

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List of symbols

A_p - Effective area of the profiled sheet (mm^2)
b - Width of the profiled sheet (mm)
d_p - Distance from top of the slab to centroid of the effective area of sheet (mm)
V_t - Experimental shear force (N)
L_s - Shear span (mm)
m - Slope of the ultimate shear bond regression line
k - Intercept of the untimate shear bond regression line
h_c - Thickness of the slab above the ribs of the profiled sheeting
h_p - Depth of the profile sheet

Appendix-1

The following are the properties of the embossed sheet provided by the manufacturer

Length of the sheet	= 3100 mm
Width of the sheet	= 900 mm
Spacing of web embossments	= 50 mm
Spacing of flanges embossments	= 30 mm
Size of web embossments	= 40 × 10 mm
Size of Flange embossments	= 15 × 10 mm
Thickness of the sheet	= 0.8 mm
Effective area of cross section of the sheet	= 895.70 mm^2
Gross area of cross section of the sheet	= 1022.98 mm^2
Weight of the sheet	= 7.23 kg/m
Moment of Inertia	= 41.63 cm^4/m
Depth of Neutral Axis from top of the steel	= 28.909 mm
Shear capacity of the profile sheet	= 45.276 kN/m
Moment capacity of the profile sheet	= 3.142 kN·m
Yield stress of the sheet	= 240 N/mm^2

UY