Shear Connector Slabs
Longitudinal Shear Resistance of Sandwich Panels with Truss and Trapezoidal shear connectors

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Abstract

Sandwich panel are being extensively and increasingly used in building construction because of their reduced dead weight, energy efficiency and aesthetic appearance. These slabs can be easily handled and erected. This work presents the experimental results of effect of shear connectors on flexural behaviour of sandwich slab panels. Truss shaped and trapezoidal shaped shear connectors have been used to study the shear interaction between the top and bottom layer of concrete. Self-Compacting concrete forms the top and bottom layer of concrete with Expanded poly Styrene as the middle layer. Few recommendations on the suitability of shear connectors have been proposed. The performance of trapezoidal shear connectors is superior than the truss shaped shear connectors. The longitudinal shear transfer between top and bottom layers of concrete and middle layer of expanded poly Styrene is better in trapezoidal shear connectors. The performance was analytically studied using Ansys software which verifies the experimental results.

Keywords: Composite sandwich slab; Shear connectors; Truss and Trapezoidal shapes, Degree of Composite action, Ansys Analysis.

1.0 Introduction

Sandwich panel slabs are cost effective mainly because of their light weight. The reduced dead weight is achieved by introducing a middle Expanded Poly Styrene layer (EPS) between top and bottom concrete layers. This type of construction is more suitable for precast slabs and prefabricated construction [Benayoune et al, 2006, Jun Qi Huang et al, 2019]. Insulated concrete sandwich panels have been widely used because of their advantages of light weight and energy efficiency [Carbonari et al, 2012, Benayoune et al, 2008, Paul M Hopkins et al, 2017, Khaled et al, 2020].This will offer thermal comfort and acoustical comfort to the occupants. The thermal resistance of sandwich slabs with EPS layer has been experimentally studied by Xiangyang et al, 2015. The thermal performance of sandwich slabs is also proved by Esteban et al, 2019. The sandwich panels also exhibit high lateral resistance when they are used as wall panels [Gang Xu et al, 2020]. The sandwich slab panels have congested shear connector arrangement in which the use of Self Compacting Concrete (SCC) prove to be vital [Vivek et al, 2017, Deepankar et al, 2018, Aarthi et al, 2018]. This type of panels are energy efficient and easy for handling and erection. The interaction between the top and bottom layer of concrete can be achieved by connecting shear connectors. The traditional types of truss shape shear connectors are very common in these types of panels. The inclined steel connectors are efficient especially when the slab is subjected to bending loads. Bush and Stine, 1994 have studied the effect of truss shaped shear connectors on the flexural strength of sandwich panels and concluded that the when the truss shaped shear connectors are placed along the longitudinal direction the composite stiffness and composite flexural strength increases.

Daniel et al, 2016 have concluded that when the sandwich panels are tested under four point bending test the failure will be predominantly by combined shear and flexural stresses. Daniel et al, 2019 have also studied the effect of wire mesh along with truss shaped shear connectors and concluded that the size of wire mesh and panel thickness are important parameters to be considered. Experimental studies have been conducted [Benayoune et al, 2006] on the effect of number of shear connectors and spacing of shear connectors on shear transfer efficiency of these panels. The angle of shear connectors is important while studying the shear transfer capacity of panels. Carbonari et al, 2012 have studied the flexural performance of 90 deg shear connectors which are straight. But definitely the straight shear connectors reduce the shear transfer capacity of slab panels. Benayoune et al, 2006 have studied the effect of truss shape connectors combined with straight 90 deg shear connectors. Noridah et al, 2016 have studied double shear connectors and have concluded that the flexural strength increases by using double shear connectors.

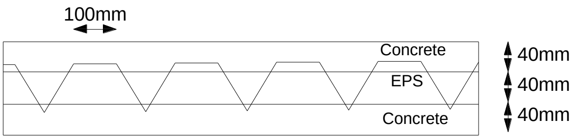
The truss shaped shear connectors increase the congestion of reinforcement within the sandwich slabs. Also the production process is difficult for this type of inclined truss shaped shear connectors. In this work the efficiency of trapezoidal shaped shear connector is tested experimentally. The production of trapezoidal shaped shear connectors is comparatively easier than the truss shaped connectors. The sandwich slabs were cast with self compacting concrete layers at top and bottom with expanded poly styrene layer at the middle part of the slab. Since the application of sandwich slabs are mostly for precast slabs, the production easiness and efficiency become important points to be considered.

2.0 Materials and Methods

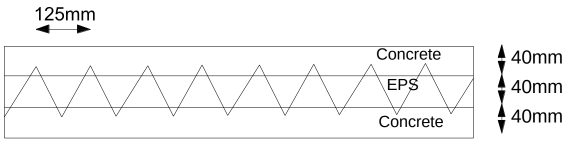
A total of six sandwich slabs were tested three with truss shaped shear connector and another three with trapezoidal shaped shear connector. The slabs were one way slabs. The slabs have a dimension of 2200mm x 750mm x 120mm as shown in the testing setup in Figure 1.

Figure 1 Testing setup

The top and bottom layers of concrete is reinforced with 8mm diameter bars at 150mmc/c in longitudinal direction and 6mm diameter bar with 250mmc/c in transverse direction. The shear connectors are also placed along the longitudinal direction. The projection of the shear connectors within top and bottom concrete is 15mm. The top and bottom concrete layers have a thickness of 40mm and the middle EPS layer has a thickness of 40mm. The angle of inclination for both shear connectors is 45 deg. Figure 2 shows the specimen details for truss and trapezoidal shear connectors. The experimental set up is shown in Figure 3.



(a)



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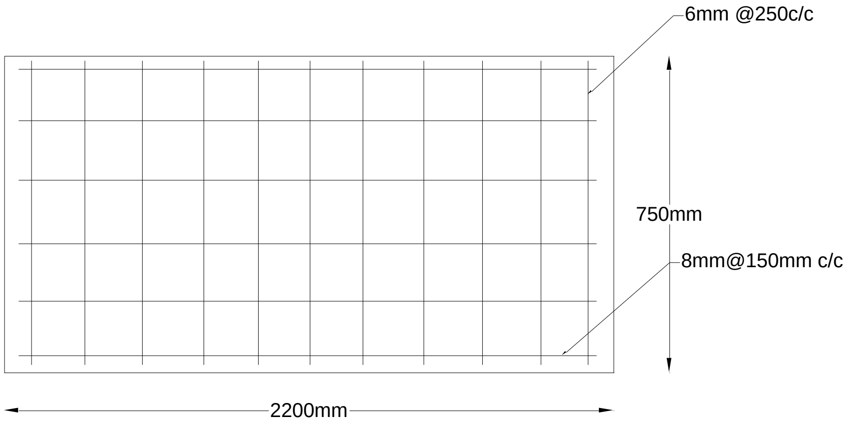


(c)

Figure 2a) Trapezoidal shape Cross section 2b) Truss shape cross section 2c) Reinforcement details

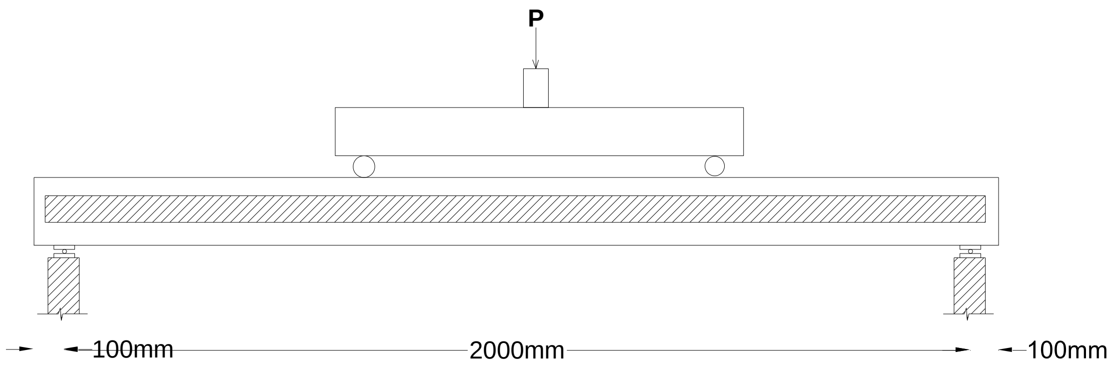


Figure 3 Experimental Set up

The form work was cleaned before casting the specimen. The concrete was then poured to form 40mm as bottom layer and surface was finished. The expanded polystyrene layer along with reinforcement was kept over the bottom layer of concrete by maintaining projection of reinforcement as 15mm within the bottom layer as shown in Figure 4. Then the top layer concrete of 40mm thick was laid. The slab is subjected to four points bending with two point loads positioned at one third distances. The supports being roller on one side and hinge on the other side. The span of the slab is 2000mm. One LVDT at mid span and one at one third span connected to the data logger were used to measure the deflection. The load was applied at small increments until failure using a 100kN load cell connected to the data logger. The crack patterns, first crack load and ultimate load were observed. The ultimate failure load is identified when excessive crack occur at the bottom layer, applied load drops and deflection increases unboundly.

Figure 4 Truss shaped Shear Connector with EPS layer before casting

2.1 Fresh and Mechanical properties of SCC

Ordinary Portland cement of 53 grade conforming to IS: 12269-2013 with specific gravity 3.12 was used to develop the self compacting concrete. The class C fly ash with a specific gravity of 2.1, 20% by volume of powder was used in order to meet the required workability criteria as per EFNARC standards. Natural river sand of specific gravity 2.61 was used as fine aggregate. Coarse aggregate of maximum size 12mm with a specific gravity of 2.68 was used. Sulphonated naphthalene polymer based super plasticizer conplast SP 430 was used at a dose of 1.5% of weight of powder.

Table 1: Mix design

Powder (Cement + Fly ash)	Fine Aggregate	Coarse Aggregate	W/C
1	2.01	1.72	0.39

Table 2: Fresh SCC properties

Sl.No	Test Method	Standard Values	Values Obtained
1	Slump flow	650-800 mm	690 mm
2	T50 cm Slump flow	2-5 Sec	4sec
3	V-funnel	6 – 12 sec	10sec
4	J-ring	0 – 10 mm	9 mm
5	L-box	H2/H1= 0.8 – 1.0	0.8
6	U-box	H2 – H1 =30 mm	27mm

Table 3 Compressive strength of SCC at 7 days and 28 days

Size of Specimen (mm)	Load at Failure (kN)	Compressive Strength at 7 days (N/mm^2)	Load at Failure (kN)	Compressive Strength at 28 days (N/mm^2)
	850	37.78	960	42.67
150 x 150 x 150	800	35.56	957	42.53
	840	37.33	960	42.67

Table 4 Split tensile strength of SCC at 7 days and 28 days

Size of Specimen (mm)	Load at Failure (kN)	Split tensile Strength at 7 days (N/mm^2)	Load at Failure (kN)	Split tensile Strength at 28 days (N/mm^2)
	183	2.6	261	3.7
(π x 150 x 300)	170	2.4	268	3.8
	170	2.4	247	3.5

Concrete cubes were prepared at the same time of casting the slab and cured at the same conditions. The composite sandwich slabs were cured by membrane curing and the water was sprinkled daily to keep the specimens in a moist condition. The average compressive strength of proposed SCC at 7 days is 36.89 N/mm^2 and at 28 days is 42.62 N/mm^2. The average Split Tensile strength of proposed SCC at 7 days is 2.47 N/mm^2 and at 28 days is 3.67 N/mm^2.

2.2 Analytical Investigation

Foam is a light weight material and of low cost. This offers good fire resistance, thermal resistance and impact properties [Mohammed et al, 2012]. Hence it is suitable to be used as an insulation material. Because of low cost Expanded polystyrene is used as core for the sandwich slab. The slab with dimension of 2200mmx 750mm x 120mm was modelled in ANSYS. The 8 node solid 65 element was used for modelling the reinforced concrete. Beam element was used to model the steel reinforcement. Table 5 and Table 6 present the properties of concrete and steel. Table 7 presents the properties of EPS layer represented as crushable foam in the analytical model. Figure 5 shows the three dimensional model created by ANSYS.

Table 5 Properties of concrete

S.No	Material Properties	Value	Unit
1	Compressive strength	42.62	MPa
2	Elastic modulus (E)	3.2641×10^4	MPa
3	Poisson's ratio (μ)	0.2	-
4	Tensile strength	3.67	MPa

Table 6 Properties of reinforcement

S.No	Material Properties	Value	Unit
1	Elastic modulus (E)	2.1×10^5	MPa
2	Yield strength (f_y)	415	MPa
3	Specific weight (ρ)	78.5	KN/m^3
4	Coefficient of thermal expansion(α)	1.2×10^{-5}	/K

Table 7 Properties of EPS Layer

S.No	Material Properties	Value	Unit
1	Elastic modulus (E)	1.5	MPa
2	Density	16	Kg/m^3
3	Poisson Ratio	0.25	-
4	Damping Coefficient	0.4	-

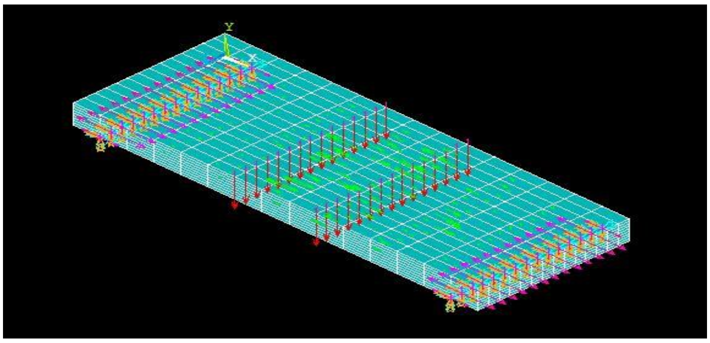


Figure 5 ANSYS model of the Slab

3.0 Results and Discussions

3.1 Experimental Results

The initial crack load, cracking moment, ultimate load, moment up to which linear behaviour was observed is given in Table 8. The values were calculated based on first principles. The cracking moment was calculated based on the distance between the load point and support. The load of the distributor beam was not considered for the calculations. The moment up to which linear behaviour was calculated based the load deflection curve.

It is observed that both panels fail by flexure. The initial crack was observed near the load point at bottom of the slab within the flexure zone. And the second crack was observed in the mid span near bottom of the slab which expanded further. Cracks at various points were observed then which lead to failure. The deflection profile of Trapezoidal shape shear connector slab in Ansys is shown in Figure 6. The crack pattern in trapezoidal shaped shear connector slab is given in Figure 7. The initial crack loads of the slabs with truss shaped shear connector were 13.28kN,12.84kN and 14.59kN. The initial crack load is almost 80% of the ultimate load 16.43kN for the specimen 1. The average value of initial crack load is 13.57kN which is 78% of the average ultimate load. The average value of initial crack load of the trapezoidal shaped shear connector slab was 18.32kN which is 66% of the ultimate load 27.59kN.

Table 8 Experimental results

Specimen No	Type of Slab	Initial crack load kN	Cracking Moment kN.m	Ultimate Load kN	Ultimate Moment kN.m	Moment up to which linear behaviour of slab was observed	Remarks
1	Truss Shape	13.28	4.43	16.43	5.48	3.98	Flexure mode of failure was observed.
2		12.84	4.28	16.99	5.66	3.91	
3		14.59	4.86	18.51	6.17	2.26	
1	Trapezoidal Shape	18.09	6.03	27.53	9.18	5.92	Combined effect of flexure and shear resulted in failure of panel
2		17.93	5.97	25.34	8.45	5.41	
3		18.93	6.31	29.91	9.97	5.92	

The moment up to which linear behaviour was observed in truss shaped connector slab was 58% of the same value in trapezoidal shaped shear connector slab. This proves that the shear transfer is effective in case of trapezoidal shaped connectors which enhanced the elastic range of load deflection curve. The Ansys model shows that the ultimate loads are 18.21kN and 28.81kN respectively for Truss and Trapezoidal shape shear connector slabs which is almost matches the average value of experimental results.

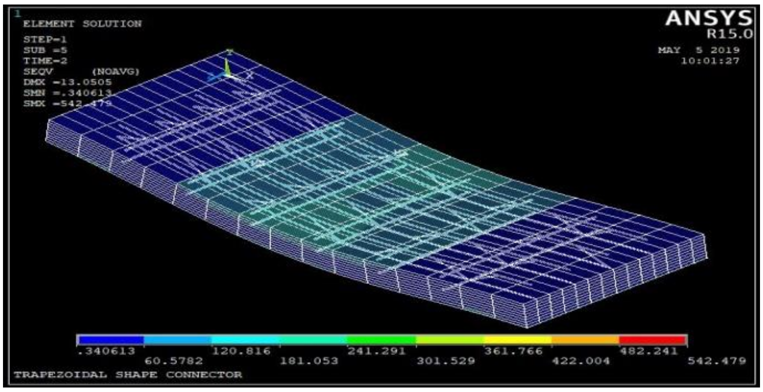


Figure 6 Deflection of Trapezoidal shape shear connector slab in Ansys

Figure 7 Crack pattern of the Trapezoidal shaped shear connector slab

It is observed that the load carrying capacity of truss shaped shear connector is lower than the trapezoidal shaped shear connector. The slab carries the transverse load by flexure and shear. The load carrying capacity in flexure depends on the longitudinal shear transfer between the top and bottom layer of concrete. Further the longitudinal shear transfer depends on the number, spacing and shape of the shear connectors used. In order to compare the effects of truss and trapezoidal shaped shear connectors the numbers and spacing of these shear connectors were kept as constant in both the slabs. The shear transfer and composite action depends on the shape of the shear connector and its bonding with the concrete.

The shear transfer between the top and bottom layer of concrete is observed to be better in the trapezoidal shaped shear connector. The easiness in casting of SCC and self compacting efficiency is improved in case of trapezoidal shaped shear connectors comparing the truss shaped shear connectors. The congestion of reinforcement in case of truss shaped shear connector can be reduced by modifying it as a trapezoidal shape. It also improves bonding in terms of contact area between the reinforcement and concrete. Hence the load carrying capacity of trapezoidal shaped shear connector slab is higher than the truss shaped shear connector slab. The load deflection and moment deflection curves for the truss and trapezoidal shaped connector slabs are given in Figure 8a to Figure 8c.

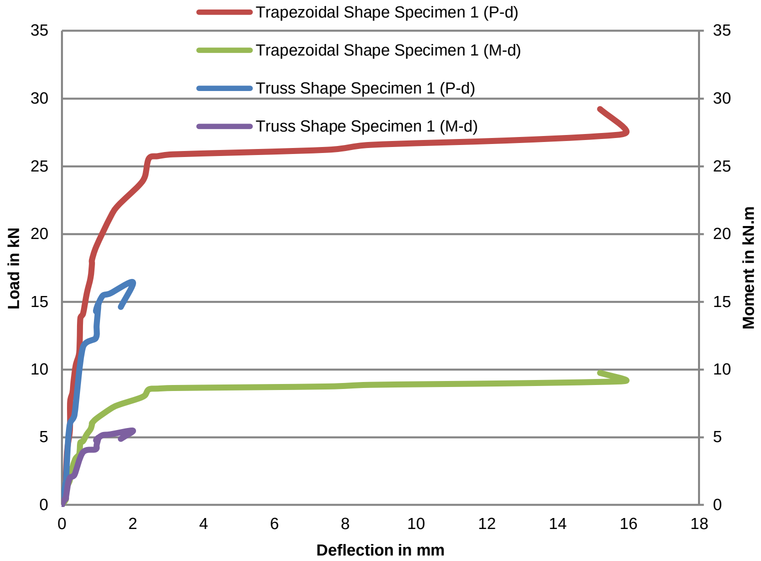


Figure 8a Load deflection and moment deflction curves for specimen 1

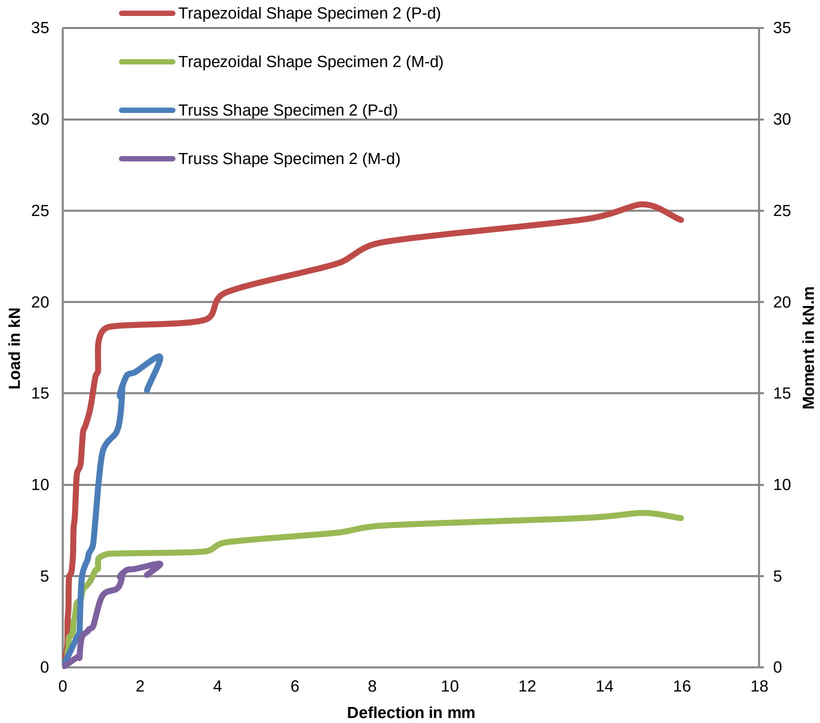


Figure 8b Load deflection and moment deflction curves for specimen 2

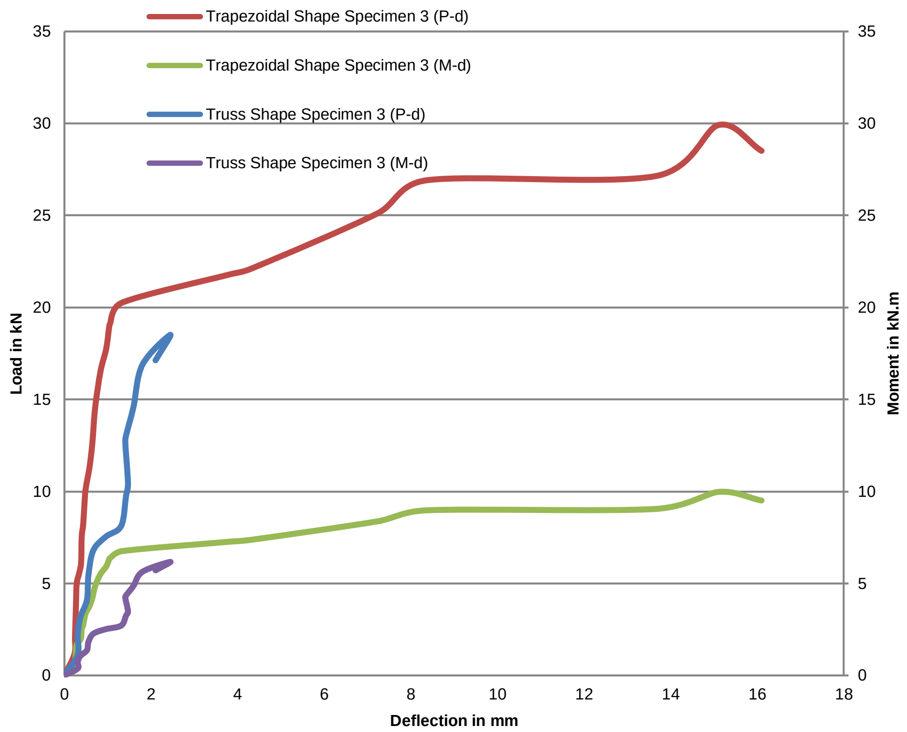


Figure 8c Load deflection and moment deflction curves for specimen 3

The sudden failure was observed in truss shaped shear connector slab. The inelastic range expanded in the trapezoidal shaped shear connector slab which was mainly because of the bonding between the shear connector and top concrete layer. The shear transfer between the bottom layer and top layer was ensured by the presence of inclined projection of connectors. The average value of ultimate load of the trapezoidal shaped shear connector slab was 27.59kN and the same for truss shaped shear connector slab was 17.31kN. The ultimate load is only 62% in truss shaped shear connector slab. The cracks were parallel to the width of the slab. All the specimens belonging to both category of the slabs developed flexural cracks at the bottom layer of concrete. Small carcks were also observed in the top layer also. The first crack was approximately at 80% for all the slabs. Eventhough the maximum bending moment was constant at middle third part of slab the first cracks were developed at the load lines along the width of the slab. At the failure load the load droped with a breaking sound. Comparing the ultimate loads of all the slabs it is evident that the trpezoidal shear connector proves to better in longitudinal shear transfer and hence there is an increase in the flexural capacity of the slab.

3.2 Analytical Calculation

The analytical flexural capacity of the slab was calculated based on linear elastic theory. The stiffness was calculated for the cross section of the slab as shown in Figure 9 and the calculated properties are given in Table 9. The calculations are valid only upto linear behviour of the slab.The stiffness of the slab was calculated neglecting moment of inertia of the EPS layer. The cracking moment is predicted based on tensile strength of concrete. The calculated deflection, calculated stiffness and calculated cracking moment are given in Table 10.

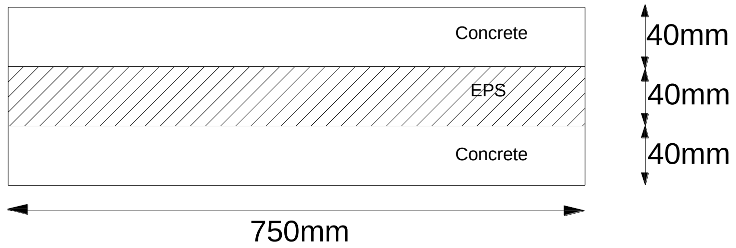


Figure 9 Cross section for calculating Flexural Rigidity

Table 9 Cross Section and Material Properties

Property	Value
Width of Panel, b	750mm
Thickness of top & bottom concrete layer	40mm
Thickness of EPS layer	40mm
Overall thickness of slab	120mm
Center to center distance of concrete layer	80mm
Moment of Inertia (neglecting EPS Layer)	104×10^6 mm^4
Elastic section modulus(Z)	1.733×10^6 mm^3
Tensile Strength of concrete	3.67N/mm^2
Flexural Rigidity (EI)	3.39×10^{12}Nmm^2

The average experimental cracking moment of truss shaped shear connector slab is 4.52 kN.m which is lesser than the calculated cracking moment. Since the analytical work considers same cross section for both the slabs the analytical cracking moments are same for both of the slabs.

Table 10 Analytical calculation of stiffness

Sl No	Type of Slab	Initial crack load kN	Calculated deflection (mm)	Calculated Stiffness (kN/mm)	Calculated cracking moment M_c (kN.m)
1	Truss Shape	13.28	1.112	11.94	6.36
2	Trapezoidal Shape	18.09	1.556	11.94	6.36

The experimental cracking moment of trapezoidal shaped shear connector slab is 6.10 kN.m which is nearly closer to the calculated cracking moment. Hence the assumption of composite action between the top and bottom layers as assumed in the calculation of moment of inertia is proved to be more valid for the trapezoidal shaped connectors slab than the truss shaped connector slab comparatively.

3.3 Degree of Composite action at ultimate stage

The ultimate flexural strength was predicted based in the following calculations for the analysed panels to determine the degree of composite action of each panel. It is impossible and a difficult task to analyse the ultimate flexural strength based on classical theories [Benayoune et al, 2008]. It is difficult to determine the degree of composite action between the top and bottom layer of concrete and to incorporate it in the transverse load carrying capacity of composite slab. However it is the usual practice to consider the two extreme cases of full interaction i,e 100% composite action and no interaction i.e 0% composite action. And the degree of composite action is determined as the ratio of experimental ultimate strength to the ultimate strength with full composite action. The degree of composite action at ultimate stage is determined using the following procedure.

When no interaction or no composite action as shown in Figure 10(a) assumed to present between the top and bottom layers of concrete the ultimate moment carrying capacity would be calculated as follows as per IS456-2000. The top and bottom layers of concrete are reinforced with 6 number of 8 mm diameter bars. A_{st} =301.6mm^2. The yield strength of steel is 415N/mm^2.

The compressive force $C = 0.364f_{ck}xb$.

The tensile force $T = 0.87f_yA_{st}$.

Where

A_{st} = Area of tension reinforcement

f_y = Yield stress in steel

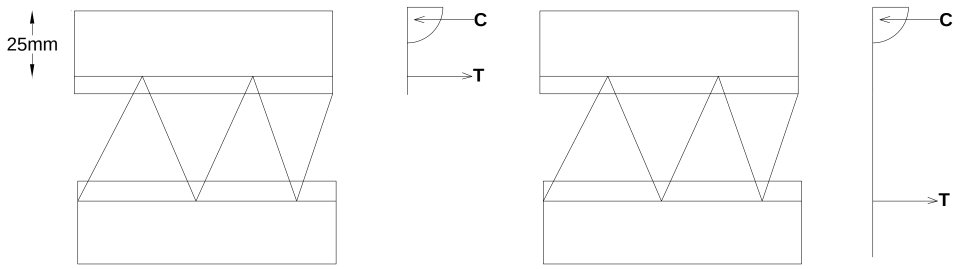
f_{ck} = Compressive strength of concrete

C = Compressive force in one layer with non composite action

T = Tensile force in one layer with non composite action

x = Depth of Neutral axis from top

At equilibrium, the depth of neutral axis is 9.35mm.The lever arm between compressive and tensile force is 21.073mm. The ultimate moment of resistance for one layer of concrete is 2.29kN.m. The total resistance of two layers with non composite action is 2 x 2.29 = 4.58kN.m. The total ultimate load carrying capacity with two point loading is P_u = 13.74kN.



(a) (b)

Figure 10a) No Composite action 10b) Full Composite action

When full composite action as shown in Figure 10(b) is assumed to present between the top and bottom layers of concrete, then the ultimate moment carrying capacity would be calculated as follows.

The lever arm between compressive and tensile force is 91.07mm in case of full composite action. The ultimate moment of resistance of concrete with full composite action is 9.91kN.m. The total ultimate load carrying capacity with two point loading is P_u = 29.73kN.

Table 8 Degree of Composite action

Experimental Ultimate Load		**Ansys Ultimate Load**		**Ultimate load by Classical method**	
Truss shape	Trapezoidal Shape	Truss shape	Trapezoidal Shape	100% Composite	0% Composite
17.31kN	27.59kN	18.21kN	28.81kN	29.73kN	13.74kN

The Table 8 shows the experimental ultimate load carrying capacity and Ansys ultimate loads of the two composite slabs along with the two extreme cases of full composite action and no composite action. The ultimate load of truss shaped shear connector slab is less by 41.7% than the ultimate load carrying capacity assuming full composite action. But the ultimate load of trapezoidal shaped shear connector slab is less by only 7.2% than the ultimate load carrying capacity by classical method assuming full composite action. If the degree of composite action is expressed as the ratio of experimental ultimate strength to the ultimate strength by full composite action than the truss shaped shear connector slab is 58.3% composite and the trapezoidal shaped shear connector slab is 92.8% composite.

4.0 Conclusion

The research work carried out to study the effect of trapezoidal shear connectors on Composite sandwich panels leads to the following conclusions

i) The trapezoidal shaped shear connectors offer high shear interaction between the top and bottom layers of concrete.

ii) The moment up to which linear behaviour was observed is 5.75kN.m in case of trapezoidal shaped shear connector slab which is higher than truss shaped shear connector slab for which it is 3.38kN.m. This proves the effectiveness of shear transfer in case of trapezoidal shaped connector.

iii) The bonding contact area between the shear connector and concrete is higher in trapezoidal shaped shear connectors which improves the shear transfer.

iv) The self-compacting efficiency is also improved due to less congestion of reinforcement in trapezoidal connectors.

v) The ultimate strength of trapezoidal shear connector slab is higher than truss shaped shear connector slab.

vi) The analytical investigation assumes full interaction between two layers of concrete which proves to be more suitable for trapezoidal shear connectors.

vii) The degree of composite action based on classical theories of reinforced concrete design, is 92.8% for trapezoidal shear connector slab.

Hence the trapezoidal shear connector reinforcement is more suitable than truss shaped connector to ensure composite action between top and bottom layers of concretes in expanded poly styrene sandwich panels.

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