Structural evaluation of Concrete Expanded Polystyrene sandwich panels for slab applications

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ABSTRACT: Sandwich panels are being extensively and increasingly used in building construction because they are light in weight, energy efficient, aesthetically attractive and can be easily handled and erected. This paper presents a structural evaluation of Concrete-Expanded Polystyrene (CEPS) sandwich panels for slab applications using finite element modeling approach. CEPS panels are made of expanded polystyrene foam sandwiched between concrete skins. The use of foam in the middle of sandwich panel reduces the weight of the structure and also acts as insulation against thermal, acoustics and vibration. Applying reinforced concrete skin to both sides of panel takes the advantages of the sandwich concept where the reinforced concrete skins take compressive and tensile loads resulting in higher stiffness and strength and the core transfers shear loads between the faces. This research uses structural software Strand7, which is based on finite element method, to predict the load deformation behaviour of the CEPS sandwich slab panels. Non linear static analysis was used in the numerical investigations. Predicted results were compared with the existing experimental results to validate the numerical approach used.

1 INTRODUCTION

Sandwich panels have been used as structural building components in various industrial and office buildings in many countries. Their uses have now been extended to residential building construction due to their ability to improve the structural and thermal performance of the houses. Sandwich panel construction in Australia has been limited to cold-storage buildings due to the lack of design methods and data. However, in recent times, the sandwich panels are extensively used in buildings, particularly as roof and wall cladding systems.

Due to considerable structural importance, a large number of publications dealing with structural sandwich panels are in existence. Rizzo & Fazio (1983) used two dimensional analysis of sandwich panel, having aluminum facings and styrofoam core, found that their analytical results will generally exceed the actual values by 15% for sandwich wall and slab panels. Sokolinsky et al. (2003) demonstrated four-point loading tests carried out on sandwich beam specimens with aluminum facesheets and a PVC foam core. The authors found that the classical sandwich theory underestimates the vertical displacements of the sandwich beam specimens by more than 20%. These evidences indicate that more research work needs to be done for understanding the behaviour of sandwich panel.

New materials and new combinations of old materials are constantly being proposed and used in sandwich panels. They have many engineering applications from wall, slab to beam. Karam & Gibson (1994) evaluated the wood-cement and natural-fibre-cement to be used as a sandwich-panel facing by performing three-point bending test. Pokharel (2003) studied the behaviour and design of sandwich panels made up of steel as a skins and polystyrene foam as a core. The author further mentioned that the structural sandwich panels generally used in Australia comprise of polystyrene foam core and thinner (0.42 mm) and high strength (minimum yield stress of 550 MPa and reduced ductility) steel faces bonded together using separate adhesives.

Schenker et al. (2005) studied the behaviour of aluminium foam protected reinforced concrete structures under impact. Vaidya et al. (2010) demonstrated the panels consisting face sheets of E-glass fibers impregnated with polypropylene matrix, while the core consists of expanded polystyrene foam developed for the exterior walls of a modularized structure. Manalo (2011) investigated the concept of glue-laminated composite sandwich beams made up of glass fibre composite skins and modified phenolic core material for railway turnout sleepers.

In this paper, a numerical approach based on finite element method was used to predict the load deformation behaviour of the concrete expanded polystyrene (CEPS) sandwich slab. The CEPS sandwich panels are made of a foam core with robotically welded steel mesh on each side and three dimensional truss system steel welded through the center foam and concrete skins. The expanded polystyrene (EPS) core provides excellent insulation against heat, sound and vibration. Besides these, EPS core also has construction viability as it provides a support mechanism for steel wire mesh for construction. Hence, concrete expanded polystyrene (CEPS) sandwich panels represent an excellent example of the optimum use of dissimilar materials.

2 EXPERIMENTAL PROGRAM

2.1 *Test Specimen*

CEPS sandwich panels reported in this research were tested in University of California, Irvine (UCI). The testing specimens included three separate CEPS sandwich panels. The diameter of the steel bar was 3 mm with the grid size of $50.8 \times 50.8\,\text{mm}$. The first panel was tested without any bottom longitudinal reinforcement bars. The cross section of the first panel is shown in Figure 1.The second and the third panels were tested with the addition of longitudinal reinforcement bars of 9.53mm and 12.7 mm respectively.

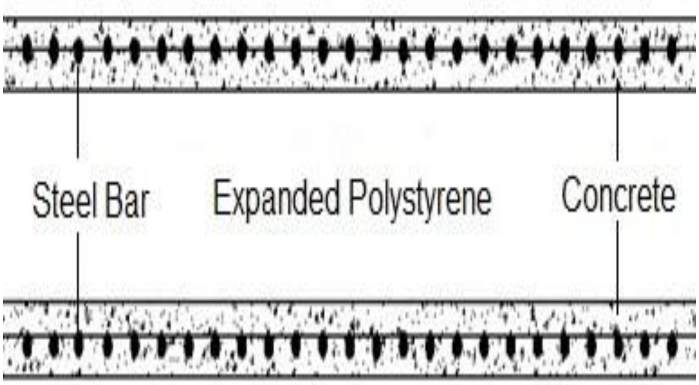

Figure 1. Schematic Cross section of CEPS sandwich panel

The details of the specimen are listed in Table 1.

Table 1. Details of testing specimens

Length (mm)	Breadth (mm)	Thickness of core (mm)	Thickness of skin (mm)	Total Thickness (mm)
3098.8	1219.2	127	44.45	215.9

Table 2 shows the compressive strength tests performed on the concrete poured on the panel for all the cases. The specimens were randomly taken in order to generalize the strength of the concrete. They were each 152.4 mm diameter by 304.8 mm high cylinders.

Table 2. Compressive Strength of Concrete

Case	Strength (MPa)
1. Without Reinforcement bars	19
2. With Reo bars of 9.53 mm	10
3. With Reo bars of 12.7 mm	10

2.2 *Test set-up and procedure*

The slab was casted using a prefabricated steel-foam sandwich panel and a concrete mix that was created on site using a mixer and pump in order to facilitate the pouring process. The panel was placed horizontally in a mould made of wooden formwork that was manufactured at UCI. The slab was tested 14 days after the initial pouring for flexure using the 4 point loading system. The slab was placed horizontally on 2 steel beams at the ends that portrayed a hinged support at each end. A 22 kN actuator placed vertically above the slab provided the load which was transferred using 2 steel cylinders connected to the actuator each 457.2 mm away from the centerline of the slab as shown in Figure 2. Both of these cylinders were rested on rubber pads along the whole width of the slab to prevent the immediate crushing of the slab at the line of contact. The deflection at the mid-span of the slab was measured with the help of spring pot placed beneath the centre line of the slab connected to the strong lab floor.

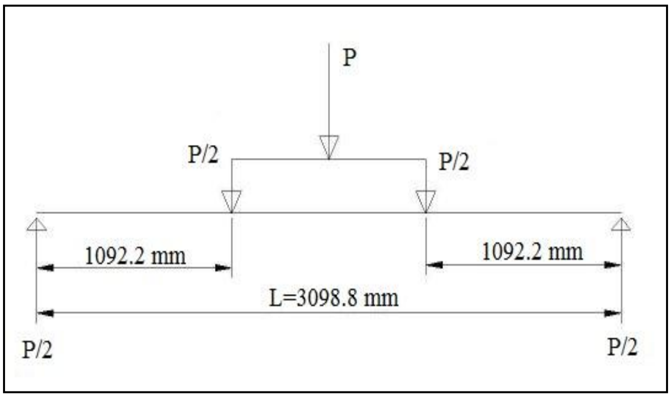

Figure 2. Loading Setup

3 EVALUATION OF FAILURE LOAD

Theoretical predictions of the failure load of the sandwich panels under flexural loads using the mechanical properties of the reinforced concrete composite skin was conducted. Since, expanded polystyrene has a very low modulus of elasticity; it is assumed that it does not provide any strength in the structure. For the simplified analysis, thus the foam is neglected. Also it is assumed that concrete does not take any tensile forces. In that case, CEPS can be analysed as a simple reinforced concrete beam.

AS3600-2009 takes the ultimate concrete strain of 0.003 which is conservative but yet reasonable. Further, the maximum allowable concrete stress of 0.85 f'_c is compatible with the ultimate strain. By considering the equilibrium of horizontal forces,

$$C_c + C_s = T \tag{1}$$

where C_c = Compressive force in concrete; C_s = Compressive force in steel and T = Tensile force in steel.

With the forces calculated, M_u is obtained by

$$M_u = C_c(d - \frac{\gamma d_n}{2}) + C_s(d - c) \qquad (2)$$

where γ = Compressive stress block factor taken as

$$\gamma = [0.85 - 0.007(f'_c - 28)] \qquad (3)$$

c = the effective cover of the reinforcing steel

The maximum bending moment is given by

$$M = \frac{P}{2} * L_1 \qquad (4)$$

where P = Ultimate load and L_1 = 1092.2 mm as shown in Figure 2.

Equating equation (2) and (4), the ultimate load from the simplified method was calculated which is shown in Table 3. It indicates that a simplified analysis is much more conservative. In all the three cases, the value of ultimate load from simplified method lags the experimental failure load by approximately 10kN.

Table 3. Comparison of ultimate load between experimental and simplified method

Case	Ultimate load	
	Experimental Setup (kN)	Simplified Method (kN)
1.Without Reinforcement bars	40	27.729
2.With Reo bars of 9.53 mm	65	55.545
3.With Reo bars of 12.7 mm	88	77.668

4 FINITE ELEMENT MODELLING

Numerical simulations were carried out to investigate the behaviour of CEPS sandwich panels. Finite Element Method was used for this purpose. Finally the numerical results are compared with the experimental results for the flexural behaviour of CEPS sandwich slabs.

4.1 *Material properties*

4.1.1 *Concrete*

Concrete behaves differently under compression and tension. In compression, the behaviour of the concrete is taken as per Table 4 and, in tension, a linear elastic behaviour is assumed up to the strength of concrete in tension as per Table 5. The progressive loss of rigidity after cracking is quantified indirectly through an adaptation of the tension behaviour introducing a downward branch. This stress strain curve is based on the characteristic strength of the concrete.

Table 4. Values of the stress-strain curve for concrete in compression based on Collins & Mitchell (1994)

Paramater	Compression
Peak stress	f'_c
Peak strain	ε_{co}= 0.0015+ f'c/70000
Ultimate stress	f_{c1}=12 MPa
Ultimate strain	ε_{c1}=0.0036
Failure strain	ε_{sp}= 0.012-0.0001 f'c

Table 5. Values of the stress-strain curve for concrete in tension based on Rots et al. (1985)

Paramater	Tension
Peak stress	$f'_t = 0.625\sqrt{f'_c}$
Peak strain	ε_{ct}= 0.1 εco
Ultimate stress	f_{t1}= f't/3
Ultimate strain	ε_{t1}=2 εu/9
Failure strain	ε_u= 18 Gf/(5f'th)

where G_f= fracture energy = h_c x area under stress-strain softening diagram and h_c= crack band width.

Rashid et al. (2002) found that Poisson's ratio of concrete changes from 0.15 to 0.25. Initial Poisson's ratio is defined by Candappa (2000) as 0.15. AS3600-2009 recommends the Poisson's ratio as 0.2 for concrete.

The values of E_c defined in some standard are given below:

Australian Standard AS 3600-2009:

$$E_c = (\rho)^{1.5} \times (0.043\sqrt{f_{cm}})\ MPa \qquad (5)$$

where ρ = density of concrete and f_{cm}= mean value of the compressive strength of concrete.

The American Concrete Institute (ACI):

$$E_c = 5000\sqrt{f'_c}\ \ MPa \qquad (6)$$

where f'_c = compressive strength.

The concrete element must be capable of modeling structural behaviour both in compression and tension. The stress-strain curve for concrete used in this research is shown in Figure 3.

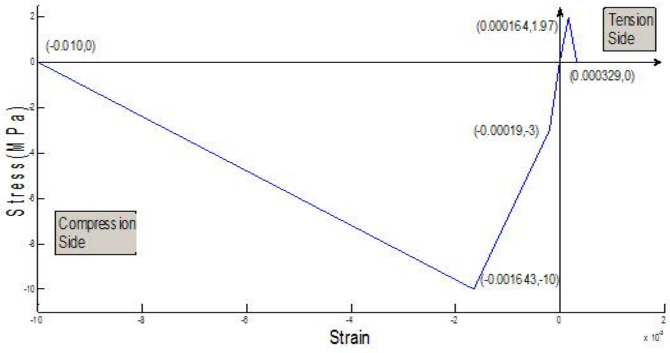

Figure 3.Stress-Strain of concrete for f'_c=19MPa

4.1.2 *Expanded Polystyrene (EPS)*

Due to the unavailability of the accurate data for the density of EPS used in the experiment, an average value of 19kg/m^3 was chosen for the analysis. . Horvath (1995) has suggested the following empirical equations for estimating the modulus of elasticity and Poisson's ratio of EPS.

$$E_{ti} = 0.45\,\rho_{eps} - 3 \tag{7}$$

$$v = 0.0056\,\rho_{eps} + 0.0024 \tag{8}$$

where E_{ti}= modulus of elasticity; v= Poisson's Ratio and ρ_{eps}=EPS density.

Since, EPS core has a very low modulus of elasticity, it was noted that the stress strain curve for EPS core does not make any difference on the model results as the value is very low compared to concrete and steel. Hence, EPS is considered as a linear material to reduce the complexity of the model.

4.1.3 *Steel*

Lloyd & Rangan (1995) assumed an idealised elasto-plastic stress-strain relationship for steel as follows:

$$f_s = \begin{cases} E_{st}\varepsilon_s & \text{if} \quad 0 \le \varepsilon_s \le \varepsilon_y \\ f_{sy} & \text{if} \quad \varepsilon_s > \varepsilon_y \end{cases} \tag{9}$$

The modulus of elasticity taken as per AS3600-2009 is 200 x 10^3 MPa for both tension and compression.

The material properties for each of the structural elements was based on the previous research conducted. These were then applied to each of the respective materials comprising the finite element models. Each of the material properties are shown below in Table 6.

Table 6. Material Properties

Material	Density (kg/m^3)	Modulus of Elasticity(MPa)	Poisson's Ratio
Concrete,f'c=19MPa	2400	22000	0.2
Concrete,f'c=10MPa	2400	16000	0.2
Steel	7850	200 x 10^3	0.25
Foam	19	5.55	0.1088

4.2 Model development

The simulations of the 4-point static bending test of the CEPS slab panels have been carried out using Strand7 finite element program. Concrete, expanded polystyrene foam and reinforcing steel are represented by separate material models which are combined together with a model of the interaction between concrete, foam and steel to describe the behaviour of the sandwich material. The concrete skin and core materials were modelled as 8-noded solid brick elements. The brick elements had aspect ratios from 1:1 to 1:1.3. The finite element model was carried out simulating the specimen and the loading set-up in the actual experimental conditions to have a reliable result. Due to symmetry, only one-fourth of the sandwich slab was modelled to reduce computational time. Figure 4 shows the numerical model used to simulate the 4-point static bending tests of CEPS slab panels.

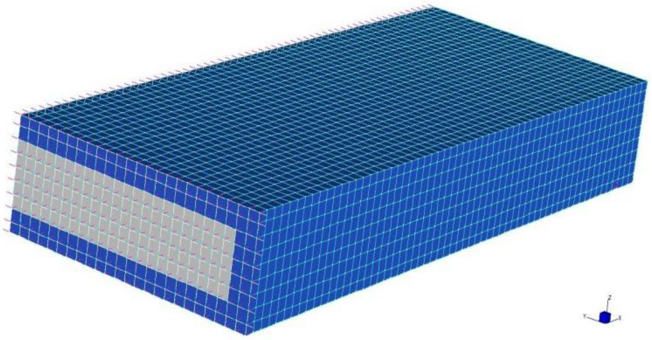

Figure 4. Quarter model of the CEPS slab panels

Non-linear analysis was conducted considering the combined effect of the non-linear behaviour of the concrete skin. The concrete and expanded polystyrene was modelled as an isotropic material. In this analysis, the Max Stress Criterion is introduced to model concrete as it can exhibit different behaviour under tension and compression. In compression, the behaviour of the concrete is taken as per Table 4 and, in tension, a linear elastic behaviour is assumed up to the failure strength of concrete in tension. For computational convenience, the steel was modelled as one dimensional cutoff bar elements. In addition, the skin was assumed to be perfectly bonded to the core, eliminating the delamination failure mode.

4.3 Finite Element Results

The typical deflection of the slab is shown in Figure 5. The panel was modeled to a quarter scale and the force applied was a quarter of the total force applied during testing.

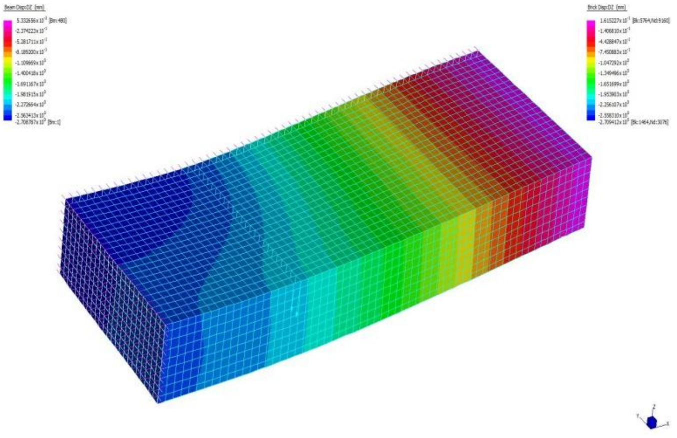

Figure 5. Deflection of CEPS panel

The maximum deflection occurred at the mid-span of the beam, which is to be expected in the four point bending test simulation. This is shown in Figure 6 by the dark blue area. The pink area represents the rising of the ends of the beam, as the load is applied in the specimens. It was observed that due to the presence of the side concrete, there is less deflection in the side of the slab than in the centre part.
The stress distribution in CEPS panels for Case 1 is shown in Figure 6.

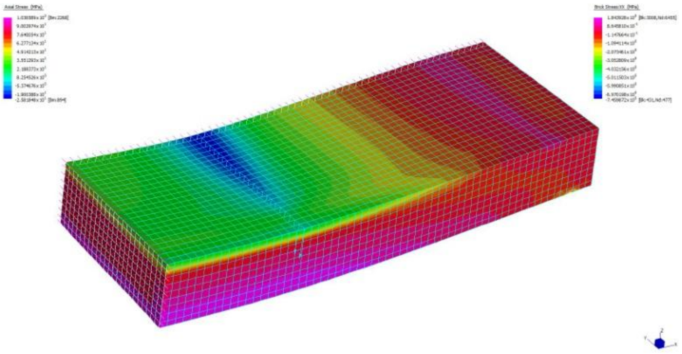

Figure 6. Stress Distribution in CEPS panels

Figure 6 shows the stress throughout the CEPS panel as the load is applied. The pink area at the bottom of the slab indicates the tensile stresses in concrete. The dark blue and green area represents the concrete in compression.

4.4 Comparison of results

A comparison of typical load versus displacement curves for all the three cases from FEA and experiments are shown in Figure 7 to 9. All these comparisons confirm that the finite element model can be satisfactorily used to analyse the load- displacement behaviour of CEPS panel used in the experiments.

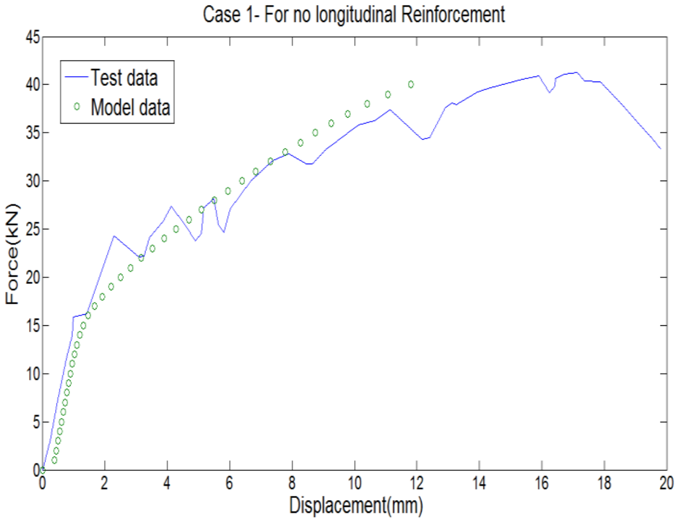

Figure 7. Comparison of Load Vs Displacement curve for no longitudinal reinforcement

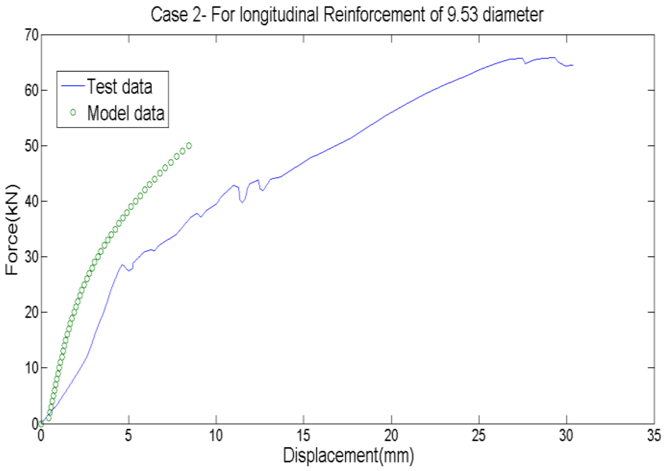

Figure 8. Comparison of Load Vs Displacement curve for longitudinal reinforcement of 9.53 mm diameter

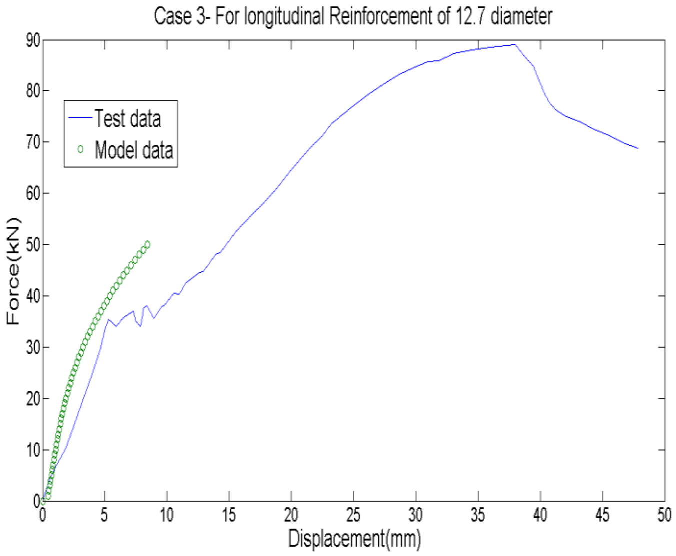

Figure 9. Comparison of Load Vs Displacement curve for longitudinal reinforcement of 12.7 mm diameter

4.5 Discussion

The purpose of the comparison of the experimental testing and finite element analysis results was to prove the excellent behaviour of the specimens during loading. The load deformation behaviour has been predicted very accurately by beam and brick finite element models.

Overall, the comparisons have been very promising, with the validity of the numerical model proven with comparison to the experimental results. Therefore the proposed model can be used to predict the strength and serviceability requirements for slab panels so that they can be used safely in slab applications.

5 CONCLUSIONS

The overall results were promising with respect to the behaviour of CEPS panels when used in a slab application. Finite element model results were in good agreement with experimental results, thus validating the prediction model.

As one of the solutions to the global environmental issue, CEPS panels can be considered as an alternate structural material to be used in structural slabs. With the use of CEPS, it not only reduces the self weight of the structure but also provides excellent insulation against sound, thermal heat and vibration. Structurally, it is important to ensure that these materials will provide the qualities of structural slabs that are required. These qualities included strength and deflection of the slab which should be within tolerable limits. This composite sandwich panel provides a promising solution for the building industry as it is light, possesses adequate strength, is relatively low cost in terms of materials and transportation and is a greener product as less concrete material is utilized.

ACKNOWLEDGEMENTS

The authors are very grateful to 3D Enbuil Advanced Building Systems Company, USA for providing the CEPS sandwich panels to be tested in the experimental component of the project at University of California, Irvine.

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