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Behavior of light weight sandwich panels under out of plane bending loading

S. Chitra Ganapathi [*1], J. Annie Peter [1a], N. Lakshmanan [1b] and N.R. Iyer [2c]

[1] *CSIR- SERC, Chennai, Tamilnadu, India*
[2] *AcSIR,CSIR- SERC, Chennai, Tamilnadu, India*

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Abstract. This paper presents the flexural behavior & ultimate strength performance of innovative light weight sandwich panels of size 3×1.2 m with two different solidity ratios viz. 0.5 and 0.33 under out of plane bending load. From the experimental studies, it is observed that the flexural strength and the stiffness are increased by about 46% and five folds for lesser solidity ratio case. From the measured strains of the shear connectors, full shear transfer between the concrete wythes is observed. The yielding occurred approximately at 4% and 0.55% of the ultimate deformation for 100 mm & 150 mm thick panels, which shows the large ductility characteristics of the panels. From the study, it is inferred that the light weight sandwich panels behave structurally in a very similar manner to reinforced concrete panels. Further from the numerical study, it is observed that the numerical values obtained by FE analysis are in good agreement with the experimental observations.

Keywords: composites; light weight sandwich panels; solidity ratio; flexural loading; experimental; finite element

1. Introduction

The profound revolutions in construction practices along with economical changes of the world and the high rate of urbanization have noticeably increased the new phase of development in construction. In recent, as a result of widespread development in construction technology has established the demands on the development of precast light weight sandwich structural elements, since that are environmental–friendly sustainable structures than traditional constructed structures. Precast light weight sandwich elements are also offer an array of promises to solve the issue of housing problems with reduction of materials and construction time. Sandwich elements are the excellent choice to achieve extremely light-weight components and structures with very high bending stiffness, high strength and high buckling resistance. Hence this gained the extensive application within the aeronautic, marine, automotive, wind energy, sport, transportation and many other industries. In civil engineering, so far, reinforced concrete sandwich panels are only

*Corresponding author, Scientist, E-mail: chitra.ganapathi@gmail.com; chitrag@serc.res.in
[a] Chief Scientist, E-mail: jannserc@gmail.com
[b] Former Director
[c] Former Director & Distinguished Emeritus Professor

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considered as the high performance composite load bearing building elements, which are generally used as floors, walls, and roofs in residential and medium rise commercial buildings. The light weight sandwich panels are generally composed of light-weight insulating material as inner core surrounded by high strength reinforced concrete skins on all sides. These panels are lighter than conventional concrete panels by about 45% to 60%, but behave structurally in a very similar manner to solid reinforced concrete panels. The reduced weight of light weight sandwich panels makes it highly preferable for structures in seismic zones, because of the reduced dynamic actions. The panels when joined together form an enclosure for multi-storied buildings and can carry gravity and lateral loads efficiently with high ductility, thus eliminating the need for a column-beam system. In view of the above, the light weight sandwich type large panel systems are advantageous over the conventional building systems.

Most of the investigations, carried out on load bearing panels are related to behavior of the solid panels. Only limited research studies are reported for light weight sandwich panels. PCI Committee (1997) discussed the use of shear connectors to transfer shear forces between the two wythes. Bush and Wu (1999) discussed the closed form solution of non-load bearing semi-composite panels with truss connectors for the prediction of the deflections and flexural stresses and the results were in turn compared with the finite element analysis results. Yeomans (2002) conducted the studies on galvanized steel reinforcing bars and inferred that galvanized steel provides longer service life of reinforced concrete than ordinary steel reinforcing bars with regard to corrosion in mild to moderate corrosive environments. (Bronius *et al*. 2009) carried out an experimental investigation on the shear and flexural behavior of masonry with hollow calcium silicate blocks to assess the strength of masonry under bending and shear. (Manalo *et al*. 2010) conducted an experimental investigation on the flexural behavior of glue laminated fibre composite sandwich beams with a view of using the material for structural beams. (Du *et al*. 2012) studied the use of biofiber based paper-reinforced polymer (PRP) composites as skin materials for light-weight sandwich panel through experimental investigation. The experimental results showed that PRP composites had comparable bending rigidity and flexural load bearing capability when compared to the commercial products. (Chitra Ganapathi *et al*. 2013) studied the flexural behavior of expandable polystyrene light weight sandwich panels through experimental investigation. Wang and Shao (2014) conducted an experimental and numerical investigation on the axial compression behavior of Sixteen concrete filled square CFRP-steel tubular (S-CFRP-CFST) stub columns. Equation for calculating the load carrying capacity of the composite stub columns were presented, and the estimated numerical results were in good agreement with the experimental results. Kirkland and Uy (2015) presented an analysis of composite beams subjected to combined loadings. An analytical model was developed to investigate the effect of axial load on the flexural strength of composite beams based on a cross-sectional analysis method using a strategy of successive iterations. Results obtained from the developed model had shown an excellent agreement with the existing experimental results. Chuda-Kowalska and Garstecki (2016) carried out series of experiments to study the behavior of Polyurethane foam (PU) sandwich panels under axial compression and bending. The experiments results were showed the pronounced anisotropy of the PU foam. Hence an orthotropic model was proposed and the limitations of application of isotropic model of PU in engineering practice were also discussed. From the experimental results it is found that the panels behave structurally in a very similar manner to reinforced concrete panels. It is also observed from the literature review that there were only few experimental investigations having numerical studies on the behavior of light weight sandwich panels under flexural loading.

In the present study, innovative concept of light-weight sandwich filler systems comprising of special reinforcement detailing have been proposed and extensive experimental and numerical investigations have been carried out to study the bending behavior and ultimate strength performance of light weight sandwich panels with shear connectors under out of plane / flexural load. Further, finite element analysis is carried out by simulating the actual test conditions and the responses are compared with the experimental values.

2. Experimental investigations on light weight sandwich panels

2.1 Description and preparation of test specimens

Light weight sandwich load bearing panels are frequently subjected to lateral loads as well as moments due to eccentric gravity loads. Hence, there is need to consider the strength of light weight sandwich panels under bending. This section provides details of the experimental investigations on the bending behavior of sandwich panels for two different geometry configurations, includes description of test specimens, fabrication, test setup, instrumentation and experimental results. For bending test, sandwiched panels of size p1 (Panel 1) – 3 m × 1.2 m × 0.10m and p2 (Panel 2) – 3 m × 1.2 m × 0.15 m; with two different solidity ratios 0.5 (50/100) and 0.33 (50/150) have been considered for the present study. The solidity ratio of the specimen is defined as the ratio of the thickness of the solid region in panel to the total thickness of the panel. As shown in Fig. 1, the panel inner core consisted of expandable polystyrene (EPS) of 50 mm thickness for 100 mm thick panel and of 100 mm thickness for 150 mm thick panel and is embedded in a 3-dimensional welded wire space frame sandwiched between the two concrete layers/plates of 25 mm thickness. A square welded mild steel wire mesh of 3 mm diameter bars with 100 × 100 mm spacing is used as the longitudinal and transverse reinforcements for the top and bottom wythes, while continuous truss core shaped connectors running through the full depth of EPS inner core of the panel is used to tie the wire mesh wythe at top and bottom and then the concrete layers, so that the panel act as a composite unit. The shear connectors are made of 3 mm diameter galvanized steel bars. Apart from shear connectors, two longitudinal RC beams reinforced with 12 mm diameter main bars are provided on either ends of the panel. In addition, it is provided with 8 mm and 10 mm diameter bars at the middle of the panel on either side for

Fig. 1 Geometry of EPS inner Core with shear Connectors and test setup

Table 1 Material properties of concrete and steel

Concrete properties

Compressive concrete strength f_{cu} (MPa)	Tensile strength of concrete at failure f_t (MPa)	Elastic modulus of concrete (MPa)
40	4.43	31623

Steel properties

Steel	Yield stress f_y (MPa)	Stress at failure (MPa)	Strain at failure	Elastic modulus of steel (MPa)
Steel reinforcement	415	430	0.0425	200000
Shear connectors	500	520	0.14	200000

100 mm and 150 mm thick panels respectively. Specimens of two different solidity ratios are cast through mould by using self compacting concrete. The material properties of the concrete, steel and the properties used for the shear connectors are obtained from the laboratory tests and are given in Table 1.

2.2 Test setup and instrumentation

The cast panels are tested in one way bending with a span of 2700 mm under a flexural load (Fig. 1). The sandwich panels are tested in a testing frame of 1000 kN capacity and the frame is anchored to a strong floor. All the solidity ratio specimens are tested in the horizontal position. The panels are in one way bending with a span of 2700 mm and middle 900 mm is kept in constant bending moment under a simulated uniformly distributed line load (Fig. 1). The one way bending panels are simply supported on two shorter sides and subjected to uniformly distributed two line vertical loads across the span by using a steel spreader beams. The load followed a cyclic loading/unloading pattern, which is designed for this test. Loading and supporting systems are extended across the full width of the panel. The specimens are loaded gradually till failure with an increment of approximately 5 kN.

Electrical strain gauges are used to record longitudinal strains in the tension and compression skins and in the reinforcements. Deflection under loading points and mid span are measured by using dial gauges fixed at the centre of the panel and under the loading point and in addition the crack pattern is also noted at each load stage.

2.3 Discussion of experimental test results and cracking failure

The experimental results are analyzed for load-deflection profile, strain variation in rebars and in concrete skin from the strain gauge outputs across the panel depth and also the mode of failure pattern is discussed. Fig. 2 shows the load-deflection response of the test specimens p1 and p2 for the comparison of performance with solidity ratio. The panel depth of the specimen p1 i.e., 100 mm is slightly different from that of the panel p2 i.e., 150 mm. Figs. 3(a) and (b) show the load versus longitudinal strain response of the panels at top and bottom locations of concrete skins and reinforcement. A summary of cracking failure mode is also shown in Fig. 4.

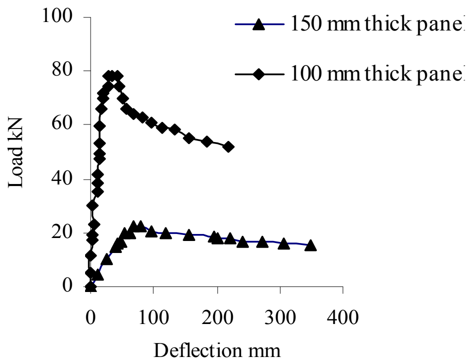
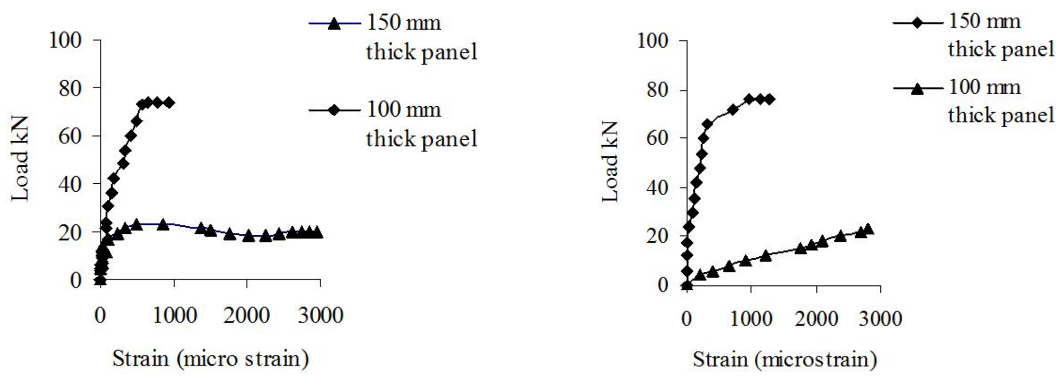


Fig. 2 Load deflection profile for different solidity ratios



(a) Concrete skin (b) Reinforcement

Fig. 3 Variation of load strain profile in concrete skin and reinforcement for different solidity ratios

Fig. 4 Failure pattern of a wall panel under flexure

2.4 Load-deflection profile

Fig. 2 clearly shows that the load-deflection behavior of all panels is approximately linear up to the yielding/first crack of concrete, regardless of the panel solidity ratio. It is further observed that after cracking, the behavior becomes nonlinear and the deflection is considerably increased till failure. The central deflection of the panel measured at the peak load (23.5 and 76.5 kN) for both solidity ratio cases is 35.54 mm and 24.05 mm. The ultimate deflection of the panel measured at the failure load for both solidity ratio cases is 315.23 mm and 215.58 mm, such a large deflection values indicate large ductility and energy absorption capacity of the panels before failure (Fig. 2). Flexural strength and stiffness of the sandwich panels are significantly affected by the increase of solidity ratio, but the peak deflection value is not much varied. The flexural strength is increased by a percentage of about 46% and the stiffness by about five folds for the lesser solidity ratio case.

2.5 Loading criteria

The first crack appeared at the bottom of the panel at a load of 18.5 kN for 100 mm and 150 mm thick panels, and the panels have failed at a load of 23.5 kN and 76.5 kN. The maximum bending moment computed at failure load is 10.3 kNm and 33.75 kNm for 100 mm and 150 mm thick panels respectively. Thus at failure, the quantified equivalent uniformly distributed load on the panels is 9.47 kN/m^2 and 37.04 kN/m^2 for 100 mm and 150 mm thick panels. The service load expected on a floor slab for a commercial building based on codal provisions is approximately 4 kN/m^2. Thus, from the test, it is observed that the panels can be used as floor panels in cases, where higher live loads are expected.

2.6 Serviceability criteria

The service loads expected on a floor slab of a commercial building is approximately 4 kN/m^2. Thus the total load on the panel works out to 12.95 kN and the maximum central deflection of the panel corresponding to the service load is of 12.7 mm for 100 mm thick panel and 1.2 mm for 150 mm thick panel. The maximum permissible deflection for slabs at service loads as per IS456:2000 (Cl.23.2) is span/250 = 2700/250 = 10.8 mm. Since the actual central deflection of 100 mm thick panel is slightly more than the acceptable value at service load, the loading is limited to 3.5 kN/m^2 over a span of 2.7 m. Thus, from the bending test, it can be concluded that the 100 mm thick panels can be used as floor panels for 1onger spans at normal live load intensity of 2 kN/m^2. In the case of 150 mm thick panel, the maximum central deflection corresponding to service load is less than the maximum permissible value. Hence, the deflection of the panel at service load is considered acceptable. Based on the load carrying capacity and central deflection, the 150 mm thick panels can be used for larger spans under a service load of 4 kN/m^2.

2.7 Strain in concrete wythes and shear connectors

Figs. 3(a) and (b) show the load versus longititudinal strain response of the panels at top and bottom locations of concrete skins and reinforcement. From the experimentally obtained strain values at top and bottom of concrete skin and from the mid rod of the panel, it is observed that the strain variation and strain discontinuity across the depth are linear and very nominal, which shows the integral behavior of the sandwich panel. This confirms the accomplishment of full shear transfer between the two wythes and also the integral behavior of two concrete wythes as a single unit to resist the loads applied till failure. The measured strains on the tensile steel reinforcement at peak load is about 900 and 700 micro strains for 100 and 150 mm thick panels respectively and thereafter, the yielding of the reinforcement has occurred. The compressive strain in the top steel reinforcement and top concrete of the panel at peak load is about 2800 and 900 micro strains for 100 and 150 mm thick panels respectively. And also from the measured strains of the shear connectors, it is observed that the legs of the truss shear connectors sensed small strains during the load transfer from the upper to lower wythe which also indicates 100% shear transfer between the wythes. The shear connectors transferred the forces from one wythe to the other efficiently till failure, which enabled the concrete wythes to maintain the composite behavior. Further, the measured strains of the gauges perpendicular to the longitudinal span i.e., on the shorter span, developed strains scarcely, which confirms the one way slab behavior similar to solid slab.

2.8 Ultimate load/crack pattern

The cracks occurred at the lower wythe of the panels are illustrated in Fig. 4. The habitual one way flexural cracking pattern is exhibited in the bottom wythe along the width of the panels. The first crack / yielding occurred approximately at 4% and 0.55% of the ultimate deformation for 100 mm and 150 mm thick panels, which shows the large ductility characteristics of the panels. The majority of the cracks are concentrated right below the applied load and in the central zone of the panel, since the maximum bending moment is at mid span and all these are in turn implied the full composite behavior of the panel. It is observed that till failure, damaged concrete is held in position by welded wire fabric which also indicates the ductility of the panels is high. Also the test panels are failed due to the yielding of tension steel (failure not by breaking of the specimen, hence, the failure is by yielding of tension) with the excessive cracks in the tension zone of the bottom wythe. The panels in turn proved to be fully composite, very ductile and consuming large deformation prior to failure.

3. Finite element analysis

Light weight sandwich panel systems require understanding into the responses of those components to a variety of loadings. Because of the complex behavior of light weight sandwich panels due to its material nonlinearity and the interaction between various components, finite element analysis is conducted. This study is largely focused the finite element model study of the light weight sandwich panel for flexural loading. Presently, there is no standard method of design for the light weight sandwich panel systems, and there are number of methods for modeling the concrete composite structures through both analytical and numerical approaches. Finite element analysis (FEA) is a numerical technique widely employed to engineering design applications which can simulate and predict the responses of complex concrete systems. The use of FEA has increased because of progressing knowledge and capability of computer software and hardware. Developments in computer capabilities are making FEA of complex structural and mechanical components more achievable. This increases the expectations of capturing the physical and mechanical effects of component details and interactions. Finite element method of analysis is an efficient way to study the performance of the panels under various loading conditions, which can help the researcher to analyze and have a better understanding about the use of panels in appropriate applications.

3.1 Finite element modeling issues

A large number of different FE formulations have been used for the analysis of concrete structural components. These may be categorized into facet plate/shell elements, thin-shell elements (Kirchhoff assumptions), thin/thick shell elements (Reissner-Mindlin theory) and three dimensional elements. The choice of an element for analysis of a structure/component depends on the geometry and the purpose for which the results of the analysis are to be used. Accurate numerical analysis of light weight sandwich panels for flexural loadings has to be based on a three dimensional model. These require considerable computational effort in terms of simulating test conditions as close as possible.

The following are some of the key aspects w.r.t modeling of light weight sandwich panels:

- Material modeling of concrete, steel and expandable polystyrene light weight inner core and shear connectors
- Modeling of uniformly distributed flexural load, incremental loads and reaction on end supports
- Employing appropriate elements such as solid and link or rebar for effective load transfer and to simulate the realistic behavior
- Simulation of material nonlinearity for larger load steps and post yield/crack regime.
- Simulation of composite behavior of light weight sandwich panels

4. FE modeling and analysis of light weight sandwich panels for various solidity ratio

Finite Element modeling and analysis are carried out for two different solidity ratios of light weight sandwich panels. The geometry of the light weight sandwich panel is shown in Fig. 5. Typical light weight sandwich panels of size 3.0×1.2×0.10 m and 3.0×1.2×0.15 m are taken for the numerical study to investigate the flexural response under out of plane bending. Creation of geometry and finite element mesh, material properties, simulation of material non-linearity, the application of boundary conditions and modeling of all loadings are carried out using a general

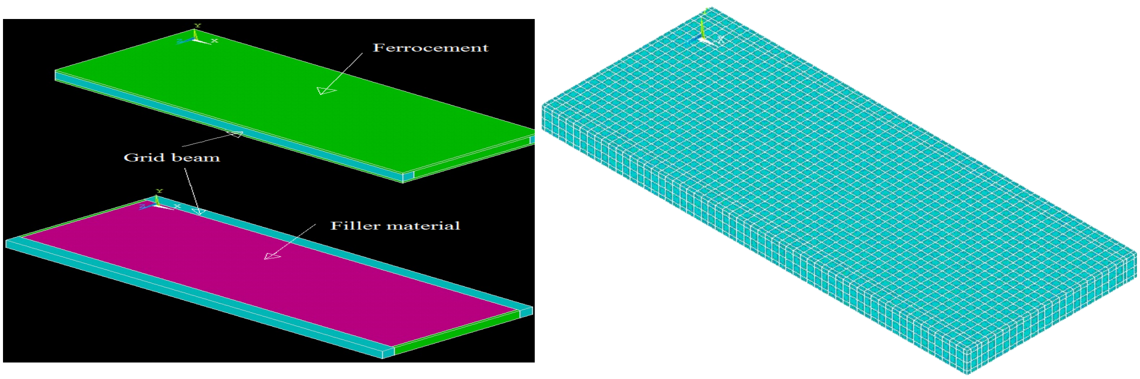


Fig. 5 Geometry and FE mesh of light weight concrete wall panel

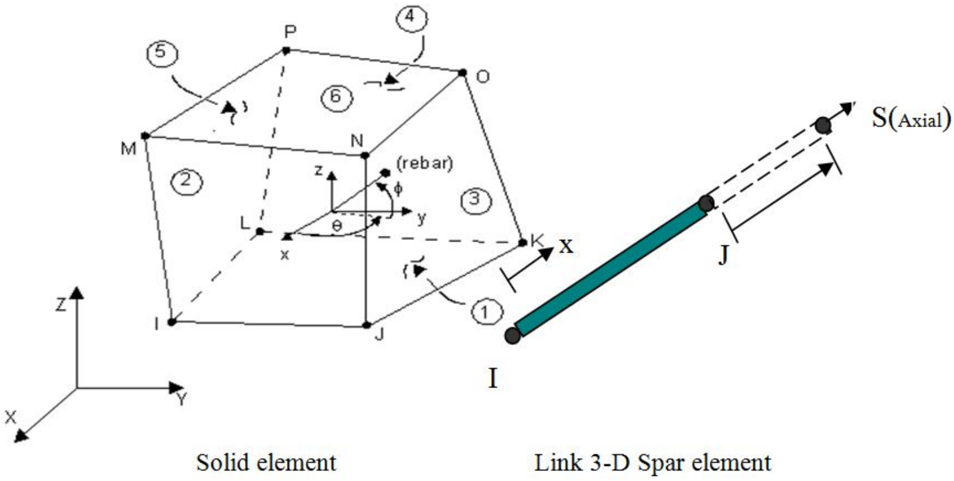


Fig. 6 FE elements used for modeling

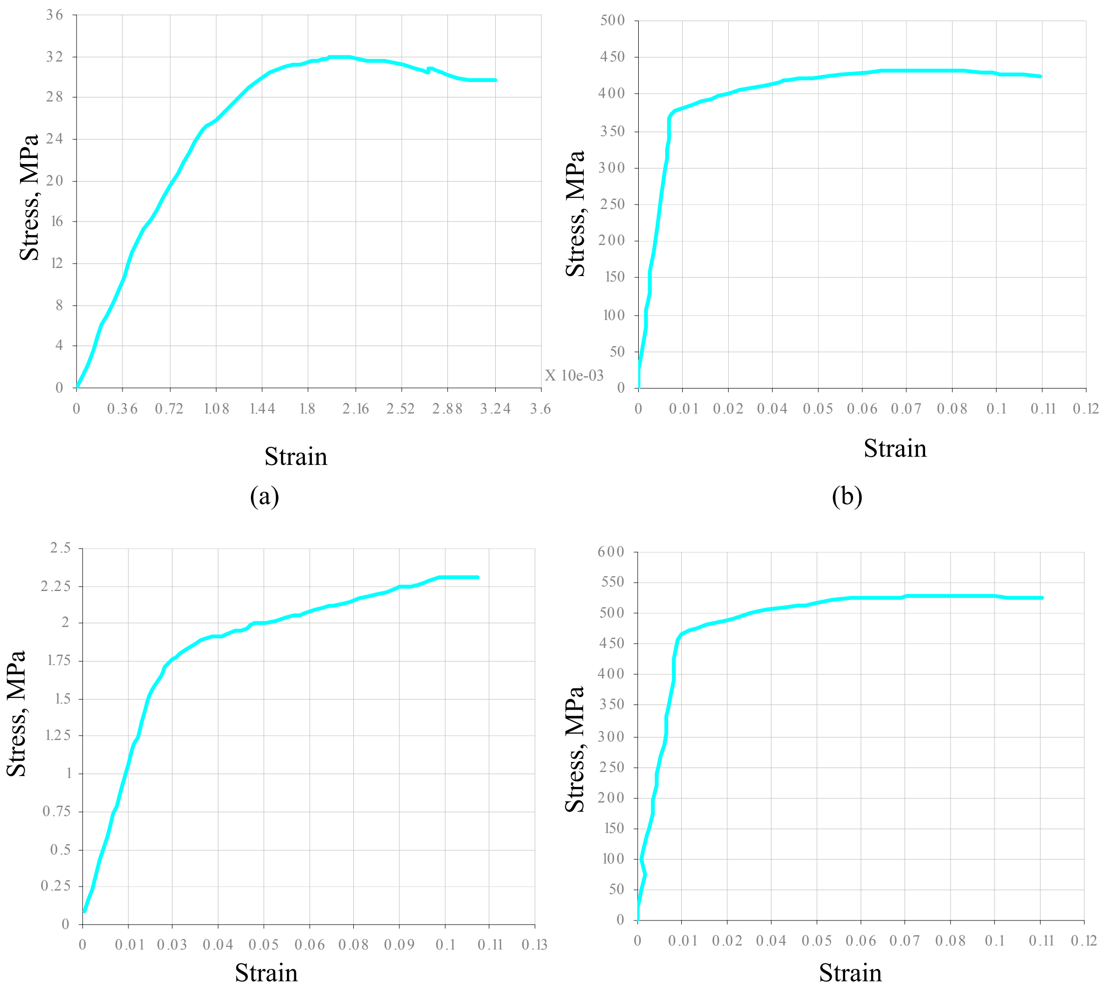
purpose finite element software ANSYS. The details of modeling are furnished below. Volume is created as per the geometry of the panels. Hexahedral solid element is employed to model the concrete layer and expandable polystyrene light weight core layer and the layers are modeled with the homogeneous isotropic material property assumption. The solid element has eight nodes with three degrees of freedom at each node i.e., translations in the nodal x, y and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions and crushing (refer Fig. 6). Link element is used to model the reinforcement. The 3-D spar element/link element is a uniaxial tension/compression element with three degrees of freedom at each node translations in the nodal x, y and z directions (refer Fig. 6). This element has plasticity, creep, swelling, stress stiffening and large deflection capabilities. Further shear connectors are also modeled by using the link element. Here, the principal function of the link element is to act as a rigid link to transfer the forces arising due to external loads. The non linear material behavior are described by a piecewise linear stress strain curve and then the panel is analyzed for static flexural load applied incrementally up to an ultimate load.

4.1 Material properties

Material properties for the concrete, mild steel, galvanized steel and light weight EPS inner core are given in Table 2. For linear static analysis, modulus of elasticity and poison’s ratio are the input values whereas for nonlinear static analysis, multilinear elastic model available in ANSYS is used. The material behavior is described by a piece-wise linear stress-strain curve, starting at the origin, with positive stress and strain values. Successive slopes can be greater than the preceding slope; however, no slope can be greater than the elastic modulus of the material. The slope of the first curve segment usually corresponds to the elastic modulus of the material, although the elastic modulus can be input as greater than the first slope to ensure that all slopes are less than or equal to the elastic modulus. Fig. 7 shows multilinear stress strain plot adopted for concrete, mild steel, galvanized steel and light weight EPS inner core material. Stress strain plot adopted for various materials is the same as that obtained from experiments.

Table 2 Material properties

Material	Modulus of elasticity, MPa	Poisson's ratio, *v*
Concrete	31623	0.15
Mild steel	2×10^5	0.3
Light weight EPS inner core	3	0.02
Galvanized steel	2×10^5	0.3



(a) (b)

(c) Light weight EPS inner core (d) Galvanized Steel

Fig. 7 Multi-linear stress strain plot

Newton-Raphson procedure is employed for nonlinear static analysis where the load is divided into series of load increments applied in several load steps. Before each solution step, out-of-balance load vector which is difference between the restoring forces corresponding to element stresses and the applied load is evaluated. Then a linear solution is carried out using out-of-balance loads and convergence is checked. When the convergence criterion is not satisfied, out-of-balance load is reevaluated, the stiffness matrix is updated and a new solution is obtained. This iterative procedure will continue until the solution converges.

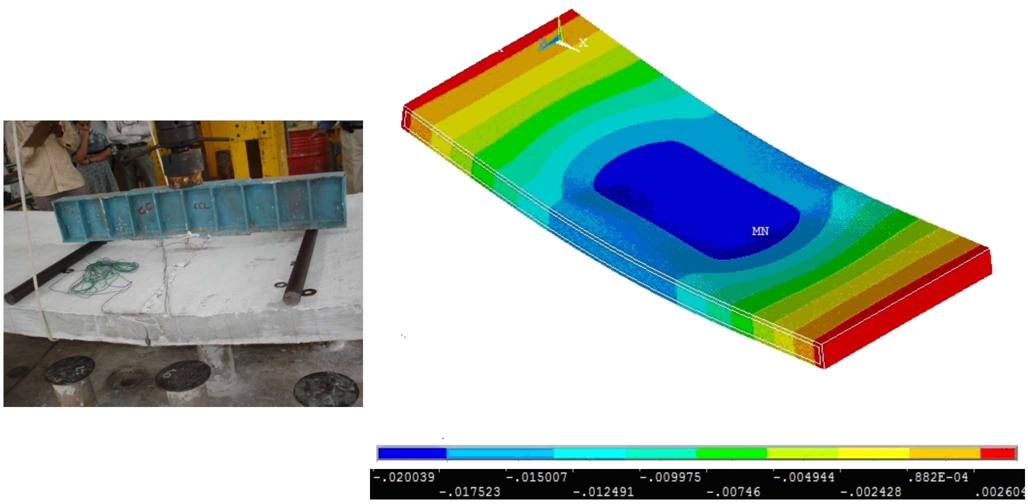
4.2 Loading and boundary conditions

As already stated, there are various loadings, namely flexural load as uniformly distributed two line vertical load is applied at nodes on the top of light weight sandwich panels across the span and the incremental load is applied gradually till failure with an increment of approximately 5 kN to failure load. Out of plane bending load or flexural load is applied incrementally on the surface of the panels to capture nonlinearities induced by material yielding at larger load. The one way bending of the panel is simply supported on two sides for the out of plane bending test.

4.3 Analysis

Linear static and nonlinear static analysis is carried out depending on the magnitude of incremental load. At each incremental load, out-of-plane deformations at centre and under the loading point are noted down. Figs. 8 and 9 show the typical out-of-plane deformation and bending stress contour for the failure load of 76.5 kN (Panel 2) respectively. From Fig. 9, it can be observed that top and bottom fibre of the wall panel experiencing maximum bending compressive stress and tensile stress as expected. It is observed that, the trend of the predicted behavior is similar to the experimental observations.

Figs. 10 and 11 show the plot of computed out of plane deformation and the corresponding experimental observation of 100 mm thick panel at centre and under loading points for different magnitudes of incremental load. The computed maximum deflection at the centre of 100 mm thick panel is 35.4 mm corresponding to the ultimate flexural load of 23 kN. It is observed from Figs. 10 and 11 that the computed deflections corresponding to each incremental load and the experimental observations are in good agreement (about 10% difference) with each other.



(a) Experimental (b) Numerical

Fig. 8 Displacement contour of the panel under flexure

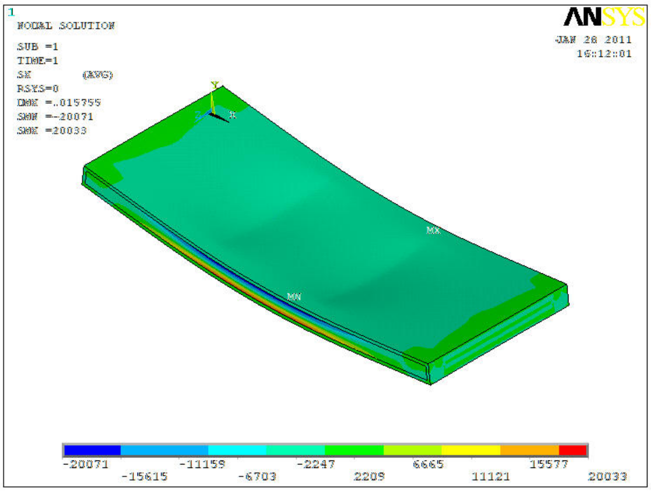


Fig. 9 Bending stress contour of the panel under flexure

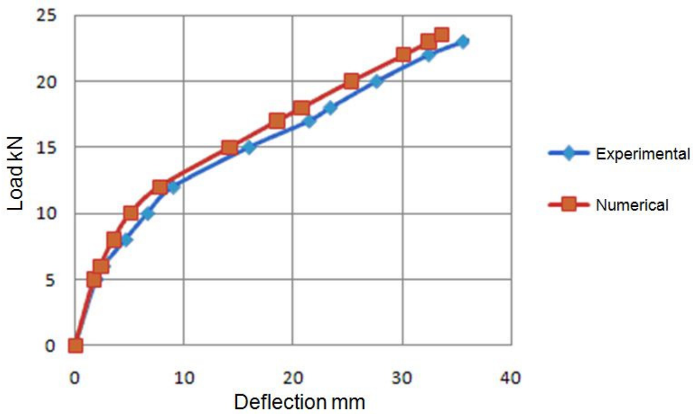


Fig. 10 Flexural load vs displacement (at centre) – 100 mm thick panels

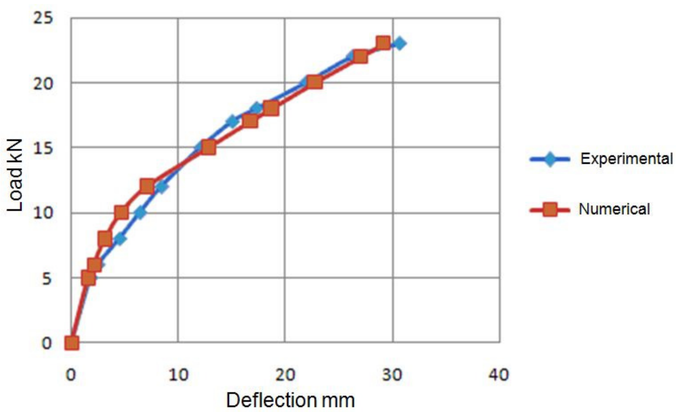


Fig. 11 Flexural load vs displacement (at load points) – 100 mm thick panels

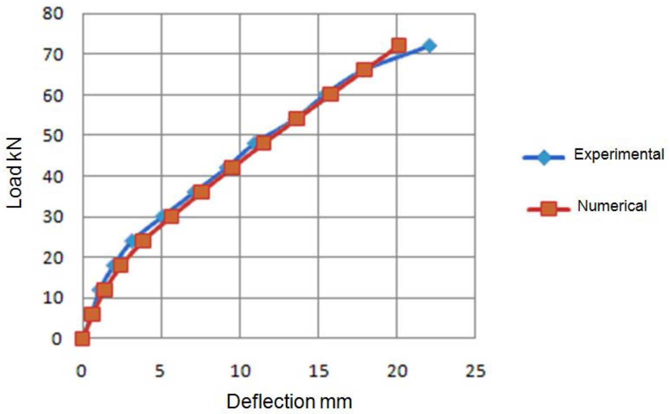


Fig. 12 Flexural load vs displacement (at centre) – 150 mm thick panels

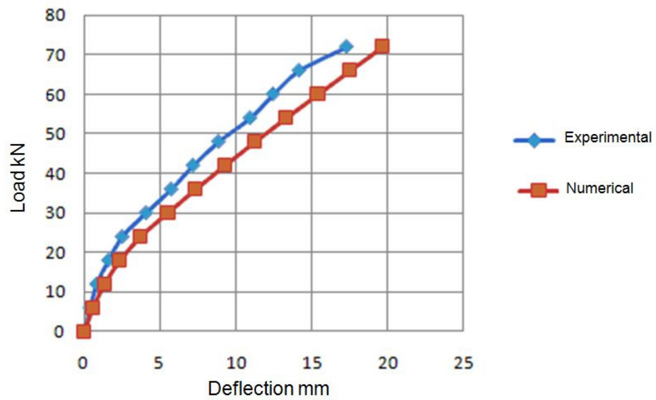


Fig. 13 Flexural load vs displacement (at load points) – 150 mm thick panels

Figs. 12 and 13 show the plot of computed out of plane deformation and the corresponding experimental observation of 150 mm thick panel at centre and under loading points for different magnitudes of incremental load. The computed maximum deflection at the centre of 150 mm thick panel is 21.8 mm corresponding to the ultimate flexural load of 76.5 kN. It is observed from Figs. 12 and 13 that the computed deflections corresponding to each incremental load and the experimental observations are in good agreement (about 5 to 10% difference) with each other.

5. Conclusions

Extensive research study has been carried out on flexural behavior of light weight concrete sandwich panels of size p1- 3×1.2×0.1 m and p2-3×1.2×0.15 m with two different solidity ratios of 0.5 and 0.33. The study includes load-deflection profile, strain variation in the rebars and concrete skin across the panel depth and the mode of failure pattern. From the experimental studies, it is observed that the flexural strength is increased by a percentage of about 46% and the stiffness by about five folds for the less solidity ratio case. Thus, from the experimentally obtained strain values at top and bottom of concrete skin and from the mid rod of the panel, the strain variation and strain discontinuity across the depth are linear and very nominal, which shows the integral behavior of the sandwich panel. This is promising the accomplishment of full shear transfer between the wythes. And also from the measured strains of the shear connectors, it is observed that the legs of the truss connectors absorbed small strains during the load transfer from the upper to lower wythe which indicates 100% shear transfer between the wythes. In all solidity ratio case panels, the habitual one way flexural cracking pattern is exhibited in the bottom wythe along the width of the panel. The first crack / yielding occurred approximately at 4% and 0.55% of the ultimate deformation for 100 mm and 150 mm thick panels, which shows the large ductility characteristics of the panels. The panels in turn proved to be fully composite, very ductile and consuming large deformation prior to failure. From the responses, it is inferred that the light weight sandwich wall panels behave structurally in a very similar manner as solid reinforced concrete panels and the reduced weight of the light weight sandwich panels makes it highly preferable for structures in seismic zones, because of reduced dynamic actions. In addition finite element modeling and analysis of light weight sandwich wall panels are presented. From the study it is observed that the out of plane displacement values obtained by FE analysis are found to be in good agreement with the corresponding experimental observations. The numerical model is quite realistic for further simulation and parametric studies to predict non nonlinear bending behavior of light weight sandwich wall panels under various load magnifications.

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