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FRP HONEYCOMB SANDWICH PANELS IN STEEL FRAMED COMPOSITE BUILDINGS UNDER EARTHQUAKE LOADING

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ABSTRACT

Modern construction technology is largely focused on the use of composite materials to build cost-effective structures as well to reduce the overall weight. Therefore, structural sandwich composite panels are nowadays widely and extensively used in aerospace, marine, building and consumer industries. Sandwich panels are lightweight and strong materials whose water and termite resistant properties are making them a very viable alternative for civil construction. Earthquake performance is one of the most important factors that can encourage wider use of composites in engineering structures. To provide an acceptable performance from the sandwich panels in the case of earthquake, its interaction with the building frame needs to be carefully examined. The paper presents the use of sandwich panels in earthquake performance can be predicted by using finite element method (FEM). In this scope, two types of steel structures, consisting of sandwich panels and concrete slabs, are modeled and analyzed using ANSYS. Finally, results are examined and compared.

Keywords: FRP-Sandwich panel, Earthquake, Finite element method, Steel framed composite buildings.

INTRODUCTION

In recent years, composite sandwich structures have found widespread acceptance in advanced structural applications ranging from aerospace to civil engineering [1]. While the primary reasons for choosing sandwich structures are their high stiffness-to-mass and strength-to-mass ratios compared to monolithic construction. Sandwich structures are geometrically more complex than monolithic beams or plates, and exhibit a very complicated behavior [2].

The structural sandwich concept involves combining of two thin and stiff faces (Fiber reinforced polymer, FRP) with a thick and relatively weak core (e.g. honeycomb). By sandwiching the core between the two faces and integrally bonding them together, a structure of superior bending stiffness and low weight is obtained. Since the core often has exceptional insulation properties, the entire sandwich structure may further be characterized by excellent thermal insulation and also acoustic damping at certain frequencies. [3, 4].

Sandwich panels comprising of flat FRP faces (skins) and a lightweight structural cores are often used as walls and ceilings in buildings where their long-span capabilities, high thermal insulation, clean design, rapid installation, and low maintenance make them the preferred choice of designers and building owners [5]. A major area where sandwich panels are beneficial is flooring systems. Due to their lightweight and strength properties, the use of sandwich panels proves a much better alternative to traditional wood or concrete flooring [6]. The reduced dead weight of the floor system results in reduced overall load and hence the need for smaller supporting members. Innovative fibre composite structural sandwich panels have recently been developed for various civil applications [7]. This new generation of sandwich panels have the potential for applications in floors, bridge decks, walls and roofs for its multifunctional structural / insulation properties.

Sandwich beams and panels have become standard lightweight structures for aerospace, naval, automotive and other applications, and have been widely studied [8-14]. This is due to their excellent properties like superior bending stiffness, low weight, excellent thermal insulation and acoustic damping, fire retardancy, ease of machining, and ease of forming among others. There are a wide varieties of core materials currently in use. Among them, honeycomb made of different materials such as aluminum, plastics, etc.; foam, balsa and corrugated cores are most widely used [15].

Sandwich panels are made of two stiff, strong skins separated by a lightweight core. By separating the skins in this way, the strength and stiffness of the structure is increased with little increase in weight. Thus sandwich panels are popular in high performance applications where weight must be kept to a minimum. In the most weight-critical applications, composite materials are used for the skins; cheaper alternatives such as aluminium alloy, steel or plywood are also commonly used. Materials used for cores include polymers, aluminium, wood and composites. To minimise weight these are used in the form of foams, honeycombs or with a corrugated construction. As well as mechanical requirements, core materials may also be selected based on their fire-resistance or thermal properties. Sandwich panels will have stiffness and strength criteria to meet many applications. The stiffness of honeycomb sandwich panels is easy to predict, but it remains difficult to estimate the strength [16].

The sandwich composites for use in steel structures are ideally made with thin face skins of fibre-reinforced polymer laminate encasing a thick core of ultra-light material. The skins are made using a wide range of fibres and polyesters, vinyl esters and epoxies. A variety of core materials are used in deck sandwich composites, with most common being polyfoam, polyurethane foam and balsa. Phenolic foams are normally used in sandwich composites requiring improved fire resistance [17].

In general, sandwich panels are loaded in the out-of-plane direction. The role of the honeycomb core in a panel is to carry shear. The stiffness of the honeycomb core in bending depends on the direction of loading and deformation of cells. Also the material properties of the cell wall play a vital role in cell deformation [18,19]. Majority of sandwich panels used for current applications use regular honeycombs. Study conducted by Evans (1991) states that, when the cell bends in the out-of-plane direction it produces a saddle shaped curvature due to in-plane poisson's ratio being positive [20].

Islam and Aravinthan investigated the behaviour of an innovative structural fibre composite sandwich panels by developing prototype two-edge and four-edge supported slab systems. Various test parameters were considered to determine the effects of varying the sandwich skin fibre orientation, the fixity between slab and joist and the slab edge support on the slab properties under point load and uniformly distributed loads (UDL). Experimental investigation suggested that fibre composite sandwich panels as slab systems behave similarly under point load and uniformly distributed load no matter the fixity, fibre orientation or slab edge support. The results of this experimental investigation show that the panels behave similarly under both loading conditions. Moreover, the fixity does not have a major effect on its failure mode and deflection [21].

Hussein investigated the behavior of sandwich panels subjected to different loading types and boundary conditions. In the study, subjects covered include laterally loaded, simply supported plates; simply supported two-span continuous plates; effects of interlayer elastic deformations on response of sandwich plates; beam-columns; local failure of sandwich panels and hydrothermal effects. To facilitate the use of solutions developed, simple formulas for the responses of sandwich panels under different loading types and boundary conditions were presented. Numerical values for the factors in these formulas were tabulated for a wide range of material properties, aspect ratios, loading types and positions [22].

Honeycomb structures are not widely used in building structures, e.g. decks. However, the recent fast growing interest in composite materials provides an opportunity for implementation of FRP-honeycomb sandwich panels. The present paper is concerned with understanding of the behavior of sandwich panel materials in framed structures. Specifically, the behaviour of composite steel framed buildings in slab systems comprising of sandwich panels and its comparison with concrete slabs have not yet been fully investigated. The aim of this study is to conduct a preliminary investigation into the effect of fire and earthquake on the edgewise compression properties and failure mechanisms of sandwich composites. In the numerical study, structural behavior of two types of sandwich panels and concrete deck which are used in a 5-storey steel framed composite buildings are modeled and analyzed using three dimensional finite element, FE software [23] and their results are compared.

FINITE ELEMENT MODEL

In order to perform the analyses, two 5-storey steel framed building models with different flooring systems were considered. In the first model (CONDECK), reinforced concrete deck, which has a wide application area in the steel framed buildings, was used, while, in the second model (SANDECK) FRP-sandwich panel was used as deck. In the model, columns were selected as HEB400 profile, primary beams and secondary beams were selected as IPE400 and IPE180 profiles, respectively. The profiles of HEB and IPE is from DIN 1025 (Deutsches Institut für Normung), EN 10034 and EN 10088-3 (European standards). In the structure, which has 3 spans in both X and Y directions, all spans are 4 m in length, the height of each storey is 3.2 m and the whole building is 16 m tall. 3D view of the corresponding steel framed building is shown in Fig. 1. A three-dimensional, non-linear finite element analysis of the 5 storey steel framed buildings under seismic loading is carried out. Analyses were performed using the general purpose finite element software ANSYS.

The materials used to prepare the finite element model consist of concrete, steel profiles and FRP-sandwich panels. Tables 1 and 2 summarize the properties of these materials. In order to obtain the actual behavior of the beam element, ANSYS model of the steel composite building is divided into bodies, nodes and elements to perform an accurate nonlinear analysis. Hex dominant finite elements are used for solid element modeling.

In the prepared model, secondary beams were connected to the primary beams by hinging and a rigid connection between beams and columns, which transfers the moment at the beam/column connection. One of the most important point is skin–core interaction in the simulation of the FRP sandwich panel, and the numerical modeling requires special attention to this interaction [24]. Within this scope, sandwich decks were modeled as three layers, upper skin, core and lower skin, and between these layers a bonding strength was described. In this way, the composite behavior of sandwich decks and the secondary and primary beams was incorporated into the model. Joints and contact regions considered in the model are summarized in Table 3. The value of live load on the decks was taken as 1.92 kN/m^2 (40 psf) and 0.96 kN/m^2 (20 psf) for normal storeys and roof storey, respectively. At all loading levels and boundary conditions, ASCE/SEI 7-10 Specification was predicated [25].

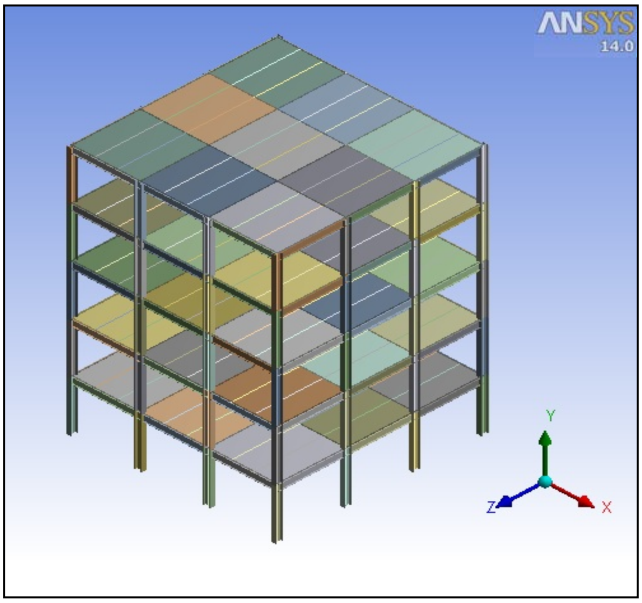

Figure 1. Five-Storey finite element model in ANSYS WB

Table 1. Material properties of steel profiles [26]

Structural steel	Weight (*kg/m*)	Density (*kg/m^3*)	Tensile ultimate strength (*MPa*)	Tensile yield strength (*MPa*)
IPE 180 (joist)	18.8	7800	400	250
IPE 400 (beam)	66.3	7800	400	250
HEB 400 (column)	155.0	7800	400	250

Table 2. Properties of FRP-Sandwich panel and concrete [*27]

Material type	Density (kg/m^3)	Modulus of Elasticity (*MPa*)	Compressive strength (*MPa*)	Tensile strength (*MPa*)	Poisson's ratio	Thickness (*mm*)
Skins (up and down)*	1425	11750	194.7	239.7	0.3	2 to 4
Core*	950	1350	24.5	8.5	0.3	10 to 40
Concrete	2400	30000	30.0	5.0	0.18	80

Table 3. Joints and contact regions in the models

	Column	Beam	Beams-joist	Slab	Column-beam	Beam-slab
Joint	√	√	√		√	√
Contact				√		√

Earthquake Analyses

Earthquake analyses can be performed using different procedures. The most popular procedure is the Response Spectrum analysis (RS-analysis). The RS-analysis is inexpensive to use in terms of numerical costs as it is based on modal results. However, the spectrum solution can only show positive results, i.e. positive stresses and strains, as it only records the maximum amplitudes for each mode and the superposition of these results in turn will give the positive results [23].

There are two steps in running a response spectrum analysis in ANSYS. First, a modal analysis is to obtain the modes/eigenvalues of the structure. Second, response spectrum analysis which is done as follows:

- Calculate the participation factor for each of the structures frequencies
- Find the maximum accelerations from the given Response Spectrum (for each mode)
- Scale the modal displacements found in the modal analysis to physical mode shapes based on acceleration, participation factors and angular frequencies.
- Finally superpose these modal results to the final result using i.e. the SRSS (square root of sum of squares) method.

Another procedure is to perform a full transient analysis of the earthquake. Such analyses are computationally expensive. However, they will give results based on the dynamic equation of equilibrium and hence both positive (tensile) and negative (compressive) stress results will be reported. In this tutorial a shell structure will be used to show how such analysis can be run in ANSYS Workbench.

The response spectrum (RS) analysis has a great advantage and fast solution times, but also has two obvious drawbacks. First of all the methods of combining the scaled modal results will always lead to final results which are all positive. The second drawback is that the analysis must be linear. A transient analysis does not have these limitations, but on the other hand it is more costly in terms of solution times. Further, to run the transient earthquake analysis, it is necessary to artificially create the time-acceleration data in such a way that these datas should be compatible with the smoothed response specter in the frequency plane.

FINITE ELEMENT ANALYSIS RESULTS

Two types of 5-storey steel framed building model are analyzed. The weight of CONDECK building is 2130 kN while that of SANDECK building is 920 kN. The model in which the reinforced concrete deck was used was called as CONDECK, while the other model where sandwich panel deck was used was defined as SANDECK. For both models, vertical load, modal analysis and earthquake analyses were performed.

Vertical Load Analysis

Determination of the Sandwich Panel Deck Thickness

In the determination of the suitable sandwich panel thickness which to be used in the steel framed building, the extreme condition was taken as the deflection limit (L/360). The total thickness of the sandwich panels made of two skin layers and core in between them varies between 8-120 mm in the analysis. In SANDECK model, different panel thicknesses were selected and by applying a vertical load (both dead and live) analyses were performed. Maximum amount of deflection for each deck panel thickness, which was obtained by the analyses, is given in Table 4.

Table 4. Various slab thicknesses and maximum deflections for SANDECK models

Model SANDECK				
Skin thickness (mm)	Core thickness (mm)	Overall thickness (mm)	Deflection at slab, max., (mm)	Deflection limit for slab: L/360 [25]
2	10	14	41.20	11.11 (4000/360) span of slab: 4000mm
3		16	33.15	
4		18	24.55	
2	20	24	8.49	
3		26	8.43	
4		28	8.30	
2	30	34	4.34	
3		36	4.32	
4		38	4.38	
2	40	44	3.34	
3		46	3.30	
4		48	3.29	

As seen from Table 4, among different sandwich panel thicknesses examined in this study, panel with a thickness of 24 mm was the one satisfying the maximum deflection criteria. For SANDECK model, vertical load analysis, modal analysis and earthquake analysis will be performed by using this deck thickness.

Comparison of Structural Behavior

In order to compare the structural behavior of the two models in the vertical load analysis, reinforced concrete and sandwich panel deck thickness values were taken to be 80mm and 24mm for the CONDECK and SANDECK models, respectively. According to the results of vertical load analysis of the models, the structural behavior parameters of the deck and frame elements are given in Table 5.

Table 5. Analysis results of vertically loaded two building models

Model definition	Deflection at slab (mm), load=D+L	at frame (max. values)		
		Axial force (N)	Bending moment (Nmm)	Shear force (N)
CONDECK	1.31	265340	1.1805e7	6529.7
SANDECK	8.49	173490	3.7058e6	2036.8

When the deck deflection and frame reaction forces of the models under vertical loading are compared, it is seen that the deflection value of CONDECK model is lower than that of SANDECK model. Due to the differences in weight and stiffness of reinforced concrete and sandwich panel decks, different maximum axial force, bending moment and shear force formed in column-beams were attained for each model, see Table 5.

Modal Analysis

Natural building periods and frequencies belonging to two construction models to be examined by modal analysis were obtained and are given in Table 6.

Table 6. Natural building periods and frequencies for two building models

Model definition	Mode 1		Mode 2		Mode 3	
	Frequency(Hz)	Period(s)	Frequency(Hz)	Period(s)	Frequency(Hz)	Period(s)
CONDECK	2.52	0.40	2.81	0.36	4.81	0.21
SANDECK	3.81	0.26	4.04	0.25	6.63	0.15

When the natural building periods and frequencies of two corresponding models are examined, it can be seen that there is a 30-35 % difference between period values.

Transient Earthquake Analysis

In the analyses performed to present behaviors of CONDECK and SANDECK models in an earthquake, acceleration data of Kocaeli-Turkey, 1999 earthquake were used [28]. The behavior of each model in an earthquake was identified by Transient Structural Analysis, also called time-history analysis.

Table 7. Results of earthquake analysis for two models

Model definition	The story drift for the top story of the structure, (mm)	Allowable story drift (mm)
		Risk category I (ASCE, 2010)
CONDECK	32.53	$0.025h_{sx}$*=0.025x16000=400
SANDECK	308.9	
*h_{sx}: the story height below level x.		

The results of the earthquake analysis for two models are given in Table 7. As seen from the Table, the displacement of the highest point of the building is 10 times higher in SANDECK model compared to CONDECK model. However, SANDECK model still satisfies the displacement criteria depicted in the corresponding specification.

CONCLUSIONS

In this study, the behavior of the FRP-sandwich panel and concrete slabs were investigated numerically by using three dimensional FE method. In this scope, two 5-storey steel framed building models with different deck systems, called CONDECK for reinforced concrete deck and SANDECK for FRP-sandwich panel deck, were prepared and their vertical load, modal and earthquake analyses were performed. Based on the results obtained from two different models, a number of recommendations for future research and application purposes are listed below: Based on the findings of this investigation, the following conclusions can be drawn:

- Based on the analyses for maximum deflection value of the selected 5-storey building, it was found that a 2.4 cm thick sandwich panel can be used in place of a 8 cm thick reinforced concrete deck.
- There is a 30-35 % difference between natural building periods of sandwich panel and concrete deck models. It can be expressed that both two models is similar character to the behavior of an earthquake.
- According to the analyses, it was determined that if a sandwich panel deck with 2.4 cm thickness is used, the displacement of the top floor of the building is 10 times higher than the case where reinforced concrete floor is used. However, sandwich panel still satisfies the boundary condition about displacement depicted in the corresponding specification.
- In both vertical load and lateral analyses, it was observed that differences in the weight and stiffness of the reinforced concrete and sandwich panels cause some variations in the reaction values (axial force, bending moment and torsional moment) of the elements in the frames of the building.
- The all weight of SANDECK building is lighter than CONDECK building, element dimensions of SANDECK can be designed smaller cross-section than CONDECK model.
- For the case of sandwich panel usage, it should be known that the dimensions of the sections used in the building would be different than those used in the reinforced concrete building.

The proposed model can be used in further studies for investigation and evaluation of different parameters on earthquake resistance of FRP-sandwich panels in steel framed composite buildings. However, there is a need to investigate the behavior of FRP-sandwich panels experimentally and as well to have a better understanding of its behavior in slab systems.

Future studies need to address the investigation of fire resistance of sandwich panel decks as compared to reinforced concrete deck and different connection conditions of sandwich panels to the beams.

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