Structural Behaviour of Precast Lightweight Foamed Concrete Sandwich Panel under Axial Load: An Overview

S. Suryani[1] and N. Mohamad[2]

[1,2]Faculty of Civil & Environmental Engineering
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA.

Abstract: The development of precast sandwich concrete has gained acceptance worldwide in conjunction with the Industrial Building System (IBS). The advancement and improvement of using wall panel has gone through a lot of achievements through the last decade. The usage of precast lightweight sandwich panel has become the alternative to conventional construction using brick wall. The usage of this panel system contributes to a sustainable and environmental friendly construction. This paper presents an overview of the latest development in precast concrete sandwich panel as an IBS. The purpose of this paper is to provide comprehensive information on latest research development of sandwich panel for building construction purposes. The information on sandwich panel's composition, material, properties, strength, availability, and its usage as structural element are reported. An innovative concept used in the design of these systems and the use of lightweight materials is also discussed.

Keywords: Precast Lightweight Foamed Concrete, Sandwich Panel, Axial Load

1. Introduction

Construction material such as brick, timber, concrete and steels are increasing in demand due to rapid expansion of construction activities for housing and other buildings. For structure which is constructed by using conventional concrete, its self weight represents a very large proportion of the total load on the structure. Furthermore, it uses aggregate which is one of earth's natural resources. With these two reasons, there is a need for alternative system to fulfill the construction demand in term of its strength, affordability and environmental friendly.

Lightweight concrete can be defined as a type of concrete which includes an expanding agent in that it increases the volume of the mixture while giving additional qualities such as self compacting and lighter weight [1].

Foam concrete is one of the lightweight concrete and was classified as cellular concrete. It has a uniform distribution of air voids throughout the paste or mortar, while "no-fines" concrete or lightly compacted concretes also contain large, irregular voids. Table 1 shows the density classification of the concrete aggregates.

Table 1 Density classification of concrete aggregates [2]

Category	Unit Weight of Dry-Rodded Aggregates (kg/m^3)	Unit Weight of Concrete (kg/m^3)	Typical Concrete Strengths (MPa)	Typical Application
Ultra Lightweight	< 500	300 – 1100	< 7	Nonstructural insulting material
Lightweight	500 – 800	1100 – 1600	7 – 14	Masonry Units
Structural Lightweight	650 – 1100	1450 – 1900	17 – 35	Structural
Normal Weight	1100 – 1750	2100 – 2550	20 – 40	Structural
Heavy Weight	➢ 2100	2900 – 6100	20 – 40	Radiation Shielding

*kg/m^3 x 0.062 = lb/ft^3 ; Mpa x 145 = lb/in.^{2}

*Corresponding author: noridah@uthm.edu.my

penerbit.uthm.edu.my/ojs/index.php/ijie

2. Precast Lightweight Concrete Sandwich Panel

Precast concrete can be defined as a concrete member that is cast in a plant. Precast concrete sandwich panels are a layered structural system composed of a low-density core material bonded to, and acting integrally with relatively thin, high strength facing materials.

Precast Sandwich Lightweight Foam Concrete Panel, PLFP, with shear truss connectors is fabricated of two concrete wythes tied together with truss-shaped shear connectors equally spaced along the length of the panel as depicted in Figure 1. The structural behaviour of the panel depends greatly on the strength and stiffness of the connectors, while the thermal resistance of the insulation layer governs the insulation value of the panel [3].

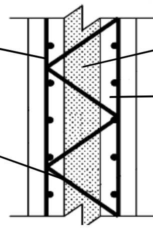

Fig. 1 Typical precast concrete with truss shaped shear connector [3]

Figure 2 shows the similar panel but with double diagonal symmetrical steel shear truss connectors. The function of these shear truss connectors is to sustain the applied load and transfer it from one wythe to the other[4].

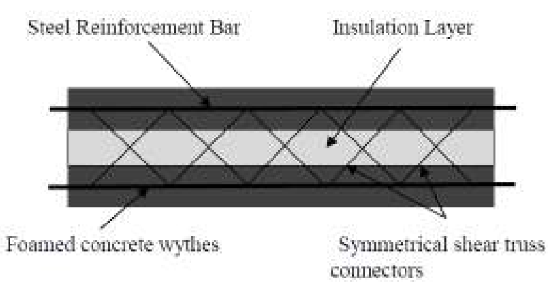

Fig. 2 Precast concrete sandwich panel [4]

Insulated sandwich panels are widely used to provide a structural shell for buildings. These panels typically consist of two layers (wythes) surrounding an insulating layer. The outer layers are usually constructed of precast or prestressed concrete and are connected through the insulation layer to form a structurally composite panel. This composite action causes the panel to deflect when the structural wythe experience differences in temperature or humidity due to the presence of the insulation wythe [5].

3. Foamed Concrete as Lightweight Concrete

Foamed concrete is a mixture of cement, fine sand, water and special foam which once harden, results in a strong, foamed concrete containing million of evenly distributed, consistently sized air bubbles and cells. In lightweight foam concrete, the density is determined by the amount of foam added to the basic cement; this way the strength of the concrete is controlled.

Foamed concrete is classified as having an air content of more than 25%. The air can be introduced into mortar or concrete mixture using two methods. First, preformed foam from a foam generator can be mixed with other constituents in a normal mixer or ready mixed concrete truck. Second, a synthetic or protein-based foam-producing admixture can be mixed with the other mix constituents in a high shear mixer. In both methods, the foam must be stable during mixing, transporting and placing. The resulting bubbles in the hardened concrete should be discrete and the usual bubble size is between 0.1 and 1 mm. The typical mixtures are as given in Table 2, which gives the range of wet density of foamed is between 500 kg/m^3 to 1200 kg/m^3. Foamed with 1200 kg/m^3 could reach up to 7.5 MPa compressive strength for 28 days and 10 MPa for 91 days. It is also shown from the table that higher density foamed concrete contains less percentage of foam volume. This means less air bubbles in the mixture which resulted with higher compressive strength.

Table 2 Typical foamed concrete mixes

Wet Density (kg/m^3)	500	525	600	1200	1200
Cement content (kg/m^3)	160	340	340	340	340
Foam Volume (%)	72	73	69	44	39
Filler Type	PFA	-	Sand	Sand	PFA
Filler Content (kg/m^3)	160	0	66	635	486
Cube Strength at 28 days (MPa)	1.0	2.0	2.0	6.0	7.5
Cube Strength at 91 days (MPa)	1.4	2.2	2.2	7.0	10.0

4. Application of Foamed Concrete Panel

Losch [6] investigated the use and benefits of precast insulated sandwich panels. It is indicated that the use of a wall panel system provides several benefits over traditional wall construction. Some of the benefits are include increased thermal efficiency, increased design flexibility, increased speed of erection and competitive costs. Figure 3 shows the basic concept of precast concrete sandwich panel.

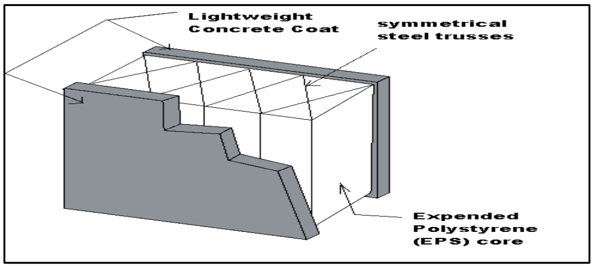

Fig. 3 Precast Concrete Sandwich Panel (PCSP)

Precast insulated wall panels have been identified to be one of the most structural efficient systems in terms of low material consumption and highly thermal efficient systems. The use of insulated precast wall panels can increase the thermal efficiency of concrete sandwich panels nearly 30 percent over that of a stud wall system [7]. These thermally efficient systems can save nearly 20 percent in energy cost compared to framed walls.

Sidney Freedman [8] stated that in the last 40 years, many tall structures have been constructed with load bearing architectural precast concrete window wall panels. Among them is the 20-story Mutual Benefit Building in Philadelphia, Pennsylvania which was built in 1969 as shown in Figure 4. Examples of load bearing sandwich window wall panel is the 20-storey Mutual Benefit Life building in Philadelphia, Pennsylvania and One Hundred Washington Square office building in Minneapolis, Minnesota, as shown in Figure.4 and Figure 5, respectively. The corner columns of these buildings have cladding at the base and then serve as insulated formwork for cast-in-place concrete for the rest of the height.

Fig. 4 Twenty-story Mutual Benefit Life Philadelphia, Pennsylvania [9]

Fig. 5 Window Wall Panels Serve as Elements Of Vierendeel Truss on One Hundred Washington Square Office Building, Minneapolis, Minnesota [9]

5. Review of Previous Studies on Concrete Sandwich Panel

The complex behaviour of PCSP due to its material non-linearity, the uncertain role of the shear connectors and the interaction between its various components has led researchers to rely on experimental investigations backed by simple analytical studies. The scarcity of information on the behaviour of this important type of construction is due to the high cost of full scale testing and the extreme difficulty of fabricating small-scale specimens.

One of the earliest studies on precast concrete sandwich panel was conducted by Pfeifer and Hanson[10]. The study included 50 reinforced sandwich panel with a variety of wythe connectors. The panels were tested in flexure under uniform loading. Test results showed that welded truss-shaped steel connectors are the most effective connection in transferring the shear force. The study also demonstrated the beneficial effect of using concrete ribs to connect the wythes.

Pantelides et al.[11], tested nine precast concrete wall assemblies with CFRP connectors. Variations in shear area and surface preparation were investigated. Test results showed that failure of the CFRP composite connection was nonductile, similar to that of the steel connection but at three times the lateral load resisted by the steel connection. The development length of the CFRP composite was found to be highly dependent on the geometry and stiffness of the connection.

Pessiki and Mlynarczyk[12] conducted lateral load tests on four full-scale precast concrete sandwich panel using different shear transfer mechanisms (region of solid concrete, wythes connectors and bond). The panels were tested in a horizontal position with simple supports under the action of a uniform lateral pressure. It was found that, for the panel geometries and materials treated in this study, the solid concrete regions provide most of the strength and stiffness that contribute to composite behavior. Steel M-tie connectors and bond between the insulation and concrete contribute relatively little to composite behavior. It is recommended for the design, solid concrete regions be proportioned to provide all of the required composite action in a precast sandwich wall panel.

Lian [13] carried out a test program to study the ultimate limit between behaviour of reinforced concrete sandwich panel under axial and eccentric loads. Four specimens were cast and tested. The ultimate load capacity for pure axial loaded panels was computed using expressions applicable to solid walls could not be directly applied to sandwich panel. It is noted that the slenderness ratio (H/t) is an important factor influencing the load bearing capacity of axial loaded panels.

A series of six precast concrete sandwich panels were cast by Adbelfattah [14] with 140 mm thick, 2.4 m long and 1.2 m wide with different reinforced concrete ribs shear connector layouts (2 identical specimens for each connectors layout). The vertical and inclined ribs were at 45^0 and 67.5^0, respectively. Each specimen was subjected to three types of lateral loading within elastic range, axial loading within elastic range and combined axial and lateral loading till failure. They were then theoretically evaluated by using STAAD III finite element software to simulate the physical tests to the elastic phase. In theoretical investigations, it was found that the contribution of the shear connectors in carrying the axial load was very small. The layout of the concrete rib shear connectors was also found to have a negligible effect on the axial capacity of the panel, within the elastic stage. It was reported that the concrete wythes carry most of the axial loads. However, these results were solely based on an elastic FEM model and were not experimentally validated as no strain gauges were placed on the shear connectors. The post-linear behaviour of the panels was not properly described.

Tarek et al.[15], investigated three different precast concrete sandwich wall panels, reinforced with carbon-fiber-reinforced-polymer shear grid and constructed using two different types of foam; namely, expanded polystyrene (EPS) and extruded polystyrene (XPS). The results of the analysis indicated that the proposed approach is consistent with the actual behavior of the panels because the predicted strains compared well with the measured values at all load levels for the different panels. Besides that, the approach is beneficial to determine the degree of the composite interaction at different load levels for different panels at any given curvature. A simplified design chart is provided to calculate the nominal moment capacity of EPS or XPS wall panels as a function of the maximum shear force developed at the interface. A simplified design chart is proposed to calculate the nominal moment capacity of EPS and XPS foam-core panels at different degrees of composite interaction. The chart is valid only for the panel configuration, geometry, materials, and reinforcement used in the current study. However, it can easily be produced for different panels. The chart demonstrates the effect of composite interaction on the induced curvature.

Frankl et al.[16], investigated six precast concrete sandwich wall panels which were designed and tested to evaluate their flexural response under combined vertical and lateral loads. The study included panels fabricated with two different insulation types: expanded polystyrene (EPS) insulation and extruded polystyrene (XPS) insulation. The panels were subjected to monotonic axial and reverse-cyclic lateral loading to simulate gravity and wind pressure loads, respectively. Based on the findings of this study, it is concluded that panel's stiffness and deflections are significantly affected by the type and configuration of the shear transfer mechanism. Percentage of composite action achieved is near 100% can be achieved with CFRP grid shear connections or with solid concrete zones. It is also found that the use of CFRP shear grid provide an effective shear transfer mechanism in precast concrete sandwich wall panels.

Oberlender[17] tested 54 wall panels with slenderness ratios (H/t_w) varying from 8 to 28 and thicknesses equal to 75 mm with hinged top and bottom edges under uniformly distributed axial and eccentric loadings. The eccentricity was applied at 1/6 of the wall thickness. The reinforcement was disposed in double layers symmetrically and separately placed within the wall thickness. The compressive cylinder strength of the concrete was between 28 and 42 Mpa and strength of steel ranged from 512.8 to 604.2 MPa. It was concluded that under axial and eccentric loading, panels with H/t_w values less than 20 failed by crushing while those with larger values of H/t_w failed due to buckling. The reduction in strength due to an eccentricity of $t_w/6$ of the wall thickness varied from 18 percent to 50 percent for variation in slenderness ratios from 8 to 28 respectively.

Based on the previous research, it is proved that the research of PLFP is still limited and there are still many weaknesses that arise such as the research done by Lian [12]. This study discussed about the ultimate limit behavior of reinforced concrete sandwich panels under axial and eccentric loads. However, the numbers of the number of tested panels was small which is only 4 specimens; therefore, no generalized inferences could be drawn. The author will test sixteen (8 by 2) panel specimens with single shear connectors and the results will be compared with the results from similar panels with double shear truss connectors tested by previous researchers. By testing higher numbers of specimen more accurate results will be recorded from the average result obtained.

From previous research, it is noticed that most of the panels developed are made of conventional concrete which made up the outer skins. This does not contribute to increase of strength over weight ratio. Therefore, further research on this type of panel with lightweight materials is very much in need. The author will investigate the structural behavior of Precast Lightweight Foamed Concrete Sandwich Panel, PLFP, with double shear truss connectors under axial Load. The aim of this research is to achieve the intended strength for use in low to medium rise building. Considering its lightweight and precast construction method, it is feasible to be developed further as a competitive IBS building system.

6. Review of Current Research

The author will investigate the structural behavior of Precast Lightweight Foamed Concrete Sandwich Panel, PLFP, with double shear truss connectors under axial load. The PLFP will be cast using foamed concrete wyhtes which enclose a polystyrene and strengthened by the shear truss connectors as shown in Figure 6. The structural behavior studied is in term of its load bearing capacity, load-deflection profile, and the strain distribution across the panel's thickness. The main aim of this research is to achieve the intended strength for use in low to medium rise building.

The capacity of PLFP panel is expected to sustain the axial load but is influenced by several factors such as compressive strength of the foamed concrete, presence of concrete capping at both ends of panel and the effectiveness of the shear truss connectors to sustain the axial load and transfer it from one wythe to the other.

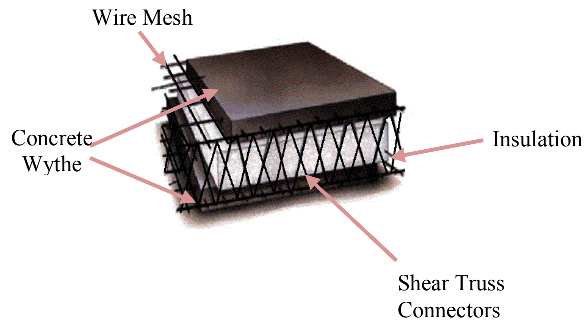

Fig. 6 Precast Concrete Sandwich Panel with Double Shear Truss Connectors

7. Experimental Programme

An experimental programme of eight (8) full-scaled specimens will be conducted to study its behaviour and axial load carrying capacity. The panels will be tested under axial load using Magnus Frame till failure.

The results will be studied in term of its load carrying capacity, load-deflection profiles, strain distribution and efficiency of the shear connectors. Various height, thickness and diameters of shear connector were used to study the influence of slenderness ratio and to find the optimum shear connector's size which ensures the stability of the panel in term of its ultimate strength and degree of compositeness achieved. The strain distribution across the panel's thickness will be used to study the efficiency and role of the shear connectors in transferring loads and to evaluate the extent of composite action achieved. The axial load achieved from the experiment will be analysed and compared with the values from classical formulae and previous researchers. The set-up of specimen and test frame is shown in Figure 7.

Fig. 7 Magnus Frame [18]

8. Conclusions

Sandwich panels have all of the desirable characteristics of a normal precast concrete wall panel such as durability, economy, fire resistance, large vertical spaces between supports, and use as shear walls, bearing walls, and retaining walls. Sandwich panels can be relocated to accommodate building expansion. In addition, the insulation provides superior energy performance as compared to many other wall systems. The hard surface on both the inside and outside of the panel provides resistance to forklift damage and vandalism and a finished product requiring no further treatment.

The results from previous research related with sandwich panel bring a lot of benefit to others which is the usage of material, manpower and cost were decreases. This proves that this material is capable and suitable to be applied in the construction industry.

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