THE STRUCTURAL BEHAVIOUR OF PRECAST LIGHTWEIGHT FOAMED CONCRETE SANDWICH PANEL AS A LOAD BEARING WALL

NORIDAH BINTI MOHAMAD

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Universiti Teknologi Malaysia

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ABSTRACT

Affordable quality housing is vital in developing countries to meet its growing population. Development of a new cost effective system is crucial to fulfill these demands. In view of this, a study is carried out to develope a Precast Lightweight Foamed Concrete Sandwich Panel (PLFP), as a new affordable building system. Experimental investigation and finite element analysis to study the structural behaviour of the PLFP panel under axial load is undertaken. The panel consists of two foamed concrete wythes and a polystyrene insulation layer in between the wythes. The wythes are reinforced with high tensile steel bars and tied up to each other through the polystyrene layer by steel shear connectors bent at an angle of 45^{o}. The panels are loaded with axial load until failure. The ultimate load carrying capacity, load-lateral deflection profile, strain distributions, and the failure mode are recorded. Partial composite behaviour is observed in all specimens when the cracking load is achieved. Finite element analysis is also carried out to study the effect of slenderness ratio and shear connectors which are the major parameters that affect the strength and behaviour of the panels. An empirical equation to predict the maximum load carrying capacity of the panels is proposed. The PLFP system proposed in this research is able to achieve the intended strength for use in low rise building. Considering its lightweight and precast construction method, it is feasible to be developed further as a competitive IBS building system.

ABSTRAK

Perumahan yang berkualiti dan mampu dimiliki adalah perlu untuk negara yang sedang membangun bagi menampung jumlah penduduk yang kian bertambah. Penghasilan sistem baru yang lebih ekonomi adalah sangat diperlukan bagi memenuhi keperluan ini. Oleh itu, kajian telah dijalankan bagi menghasilkan panel pratuang sanwic yang diperbuat dari konkrit berbusa foam (PLFP), sebagai sistem bangunan baru yang mampu dimiliki. Penyiasatan eksperimen dan analisis unsur terhingga bagi mengkaji kelakuan struktur panel PLFP yang dikenakan beban paksi telah dijalankan bagi tujuan ini. Panel ini terdiri daripada lapisan perangkap haba iaitu polisterin yang terletak diantara dua lapisan dinding konkrit berbusa foam. Lapisan dinding dikuatkan dengan besi bertegasan tinggi yang diikat kepada besi penyambung ricih yang dibengkokkan 45° dan merentasi lapisan polisterin. Panel dibebankan dengan beban paksi sehingga gagal. Keupayaan maksima menanggung beban, profil hubungan beban dan pesongan sisi, penyebaran keterikan dan mod kegagalan telah direkodkan. Kelakuan komposit separa dapat dilihat dalam semua spesimen apabila ia mula mengalami retakan. Analisis unsur terhingga dijalankan bagi menentukan pengaruh nisbah kelangsingan dan penyambung ricih yang merupakan parameter utama yang mempengaruhi kekuatan dan kelakuan panel. Persamaan empirikal diterbitkan bagi menentukan keupayaan menanggung beban maksima panel. Sistem panel PLFP yang dicadangkan dalam kajian ini mampu mencapai kekuatan yang diinginkan bagi kegunaan di dalam bangunan rendah. Memandangkan panel ini ringan dan menggunakan kaedah pembinaan pratuang, ia boleh dibangunkan lagi kerana ia berpotensi sebagai sistem bangunan IBS yang berdaya saing.

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LIST OF ABBREVIATION

CIDB	-	Construction Industry Development Board of Malaysia
IBS	-	Industrial Building System
PLFP	-	Precast Lightweight Foamed Concrete Sandwich Panel
FEM	-	Finite Element Method
PCSP	-	Precast Concrete Sandwich Panel
FRC	-	Fiber-Reinforced Composite
EPS	-	Expanded Polystyrene Panel System
PAC	-	Pumice Aggregate Concrete
HPC	-	High Performance Concrete
FRP	-	Fiber Reinforced Polymer
AAC	-	Autoclaved Aerated Concrete
BCA	-	British Cement Association
ASTM	-	American Standard Testing Method
BS	-	British Standard
UTM	-	Universal Testing Machine
E	-	Modulus Young
LVDT	-	Linear Voltage Displacement Transducer
ESG	-	Electrical Strain Gauge

LIST OF SYMBOLS

H - Height of panel

H/t - Slenderness ratio

EI - Stiffness

$EcIg$ - Gross uncracked stiffness

P_u - Ultimate strength of panel

Ø - Strength reduction factor

f_{cu} - Compressive strength of foamed concrete

A - Gross area of section

k - Slenderness Factor

t - Overall thickness of member

N - Ultimate axial load

N_{uz} - Design ultimate capacity

N_{bal} - Design axial load capacity for symmetrically reinforced rectangular section

k - Reduction Factor

A_{sc} - Area of steel

f_y - Tensile strength of steel

P_u - Ultimate axial load

A_c - Gross area of panel section

f_y - Yield strength of steel

L - Width of the panel

A_c - Gross area of the wall panel section (equal to the gross concrete area)

t_1 - Thickness of wythe

t_2 - Thickness of core layer

c - Concrete cover

f_t - Tensile Strength of foamed concrete

ε_c - Strain at peak uniaxial compression

ε_o - Strain at end of softening curve

G_f - Fracture energy per unit area

β_r - Biaxial to uniaxial stress ratio

Z_o - Initial relative position of yield surface

ψ - Dilatancy factor

m_g - Constant in interlock state function

m_{hi} - Contact multiplier on ε_o

m_{ful} - Final contact multiplier on ε_o

r_σ - Shear intercept on tensile strength

μ - Slope of friction asymptote for damage

σ_y - initial yield stress

Pt - Stress at ultimate

ε - Strain at Failure

E - Modulus Young of Steel

ρ_{wet} - Wet density of foamed concrete

ρ_{dry} - Dry density of foamed concrete

v - Poisson’s Ratio

α - Coefficient of thermal expansion

e - Eccentricity

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CHAPTER 1

INTRODUCTION

1.1 Construction Industry in Malaysia

Housing remains a major issue in Malaysia as in many other developing countries in the world. The problem is raised due to the increasing population, demands of affordable and quality houses, migration of rural masses into the city and industrial centers and also demands due to higher quality of life. The increase in housing demand during the Ninth Malaysia Plan (2006 to 2010) from the public and private sector is shown in Table 1.1. It is observed from this table that approximately 709,400 houses are targeted for different user-groups during the 5 years period.

Table 1.1: Housing Targets from the Public and Private Sector, 2006 to 2010 (Construction Industry Development Board, 2007)

Programme	*Number of houses*					*Total*	
	Housing for the poor (PPRT)	Low Cost	Medium Low Cost	Medium cost	High cost	Total units	%
Public sector	20,000	85,000	37,005	27,100	28,700	197,805	27.9
Private sector		80,400	48,500	183,600	199,095	511,595	72.1
Total	20,000	165,400	85,505	210,700	227,795	709,400	100.0
%	2.8	23.3	12.1	29.7	32.1	100.00	

It is difficult to provide solutions to this problem with the present traditional building construction systems because the traditional system is unable to meet the housing demand in a short time without sacrificing quality. Due to this inadequacy of traditional building construction systems, new technology is needed in the construction industries which can meet this requirement. Meeting the demands for higher performance, lower cost and faster projects requires transition from traditional building techniques to innovative construction methods.

Construction Industry Development Board of Malaysia, (CIDB), has produced a 10-year master plan for Malaysian construction industry for a period from 2006 to 2015. It is a comprehensive plan charting the strategic position and future direction of the Malaysian construction (CIDB, 2007). It is also aimed at supporting the nation’s economic growth as well as increasing accessibility to adequate, affordable and quality houses for all income groups, particularly the lower ones.

The planning does not only focus on improving the living standard of Malaysians, but also on harvesting the development of caring society. There are seven strategic thrusts in the Master Plan which are inter-related and together serve to achieve the overall vision. The fifth strategic thrust in the Plan is innovation through research and development and adoption of new construction method. This thrust is aimed at addressing the polemic of the local construction industry which has been characterized as labour intensive and dependent on foreign unskilled workers. As such, the construction industry needs to progress towards one that is more focused in innovation.

Industrial Building Systems or IBS is one of the innovations and is seen as one solution in the development of new technology in the construction industries. IBS utilizes techniques, products, components, or building systems which involve prefabricated components and on-site installation. It has been in existence since the 1960’s (Thanoon *et al*., 2003). However, according to the CIDB IBS Survey, less than one third of completed projects up to 2002 utilized IBS. IBS should be utilized more aggressively in the local industry because it helps to overcome problems imposed by the traditional labour intensive methods.

IBS promises numerous benefits compared to the conventional method. Its usage is usually more economical than the conventional construction system due to the following advantages (Junid, 1986, Esa and Nurudin, 1998, Lessing *et al*., 2005):

a) Standardization of sizes and materials allows faster and more accurate production with less waste.
b) More accurate scheduling can be obtained because of more predictable production.
c) The use of unskilled or semi skilled labour is possible by the simplicity and standardization of the construction technique.
d) With the use of standardization of building components, the use of Information Technology (IT) in construction can further be enhanced. IT will speed up the networking between the consultants, architects, contractors and most importantly, the clients.

In general IBS construction method leads to increased efficiency and productivity. This chapter discusses precast lightweight sandwich technology as an IBS system that has great potential to be further studied and developed in Malaysian's construction industry.

1.2 Precast Concrete Building System

Precast building system is a system where parts, members and elements of structures are produced either on-site or at the factory, and transported to the site of construction. Using concrete material, the precast component may be cast in a formwork in a position other than the actual one. After the concrete has matured, the forms are removed and the component are installed and fixed in the actual position. The benefits of precast concrete as compared to conventional system include its better quality control and, fast delivery and installation. In most cases, precast panels are cast with high quality concrete and therefore results in smooth surface appearance.

The precast building systems are mainly categorized into load bearing wall structure system (Figure 1.1(a)), and frame and skeletal structure system (Figure 1.1(b)). The structural elements of load-bearing wall structure systems consist of load-bearing walls and floors while the structural elements of frame and skeletal structure systems consist of columns, beams and floors. The frame and skeletal structure systems are utilized mainly for industrial buildings, shopping malls, car parks, sporting facilities and office buildings, whereas the load-bearing wall structures are suitable for apartment buildings, nursing homes, dormitories, and hotels (Bohdan, 1966).

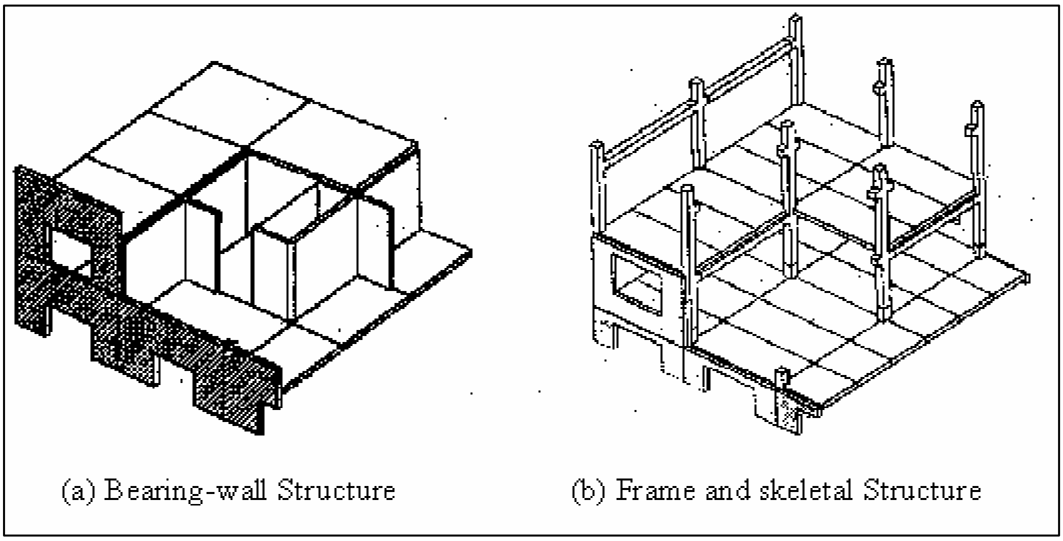
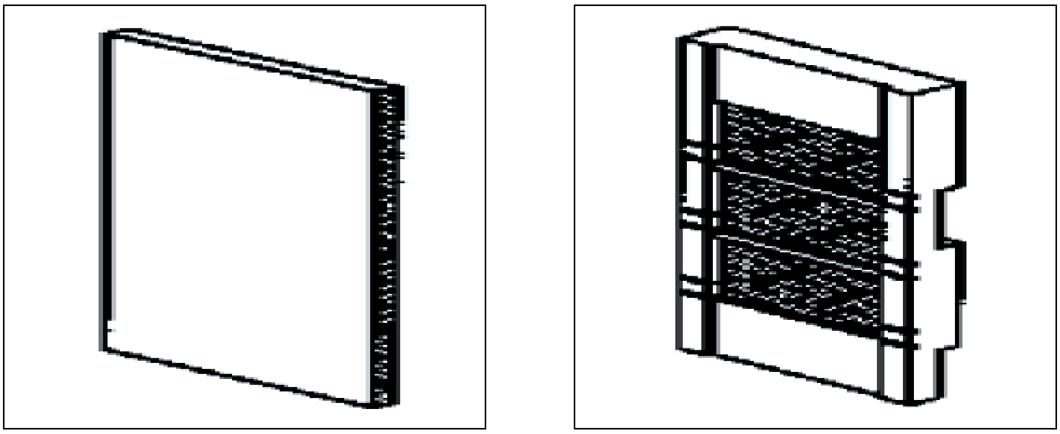

(a) Bearing-wall Structure
(b) Frame and skeletal Structure

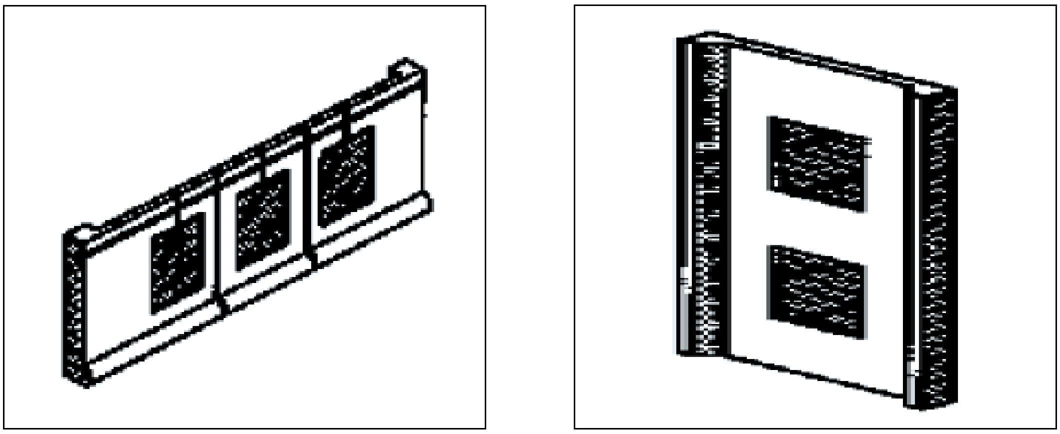
Figure 1.1: Precast Structure Systems (Bohdan, 1966)

Wall element of a building can be constructed using precast system. A precast wall system can be comprised of flat or curved panels (solid, hollow-core, or insulated), window or mullion panels, ribbed panels, or a double-tee as shown in Figure 1.2. These precast elements are normally used as cladding material which is non-load bearing (Freeman, 1999). This is due to their structural capability as load bearing elements are often overlooked. For instance, in the case of low or medium rise buildings, the amount of reinforcements required in handling and erecting cladding panels such as wall and window panels are often more than necessary for carrying imposed loads. Thus, with relatively few modifications, these panels can function as load bearing members especially in the low to medium rise buildings.



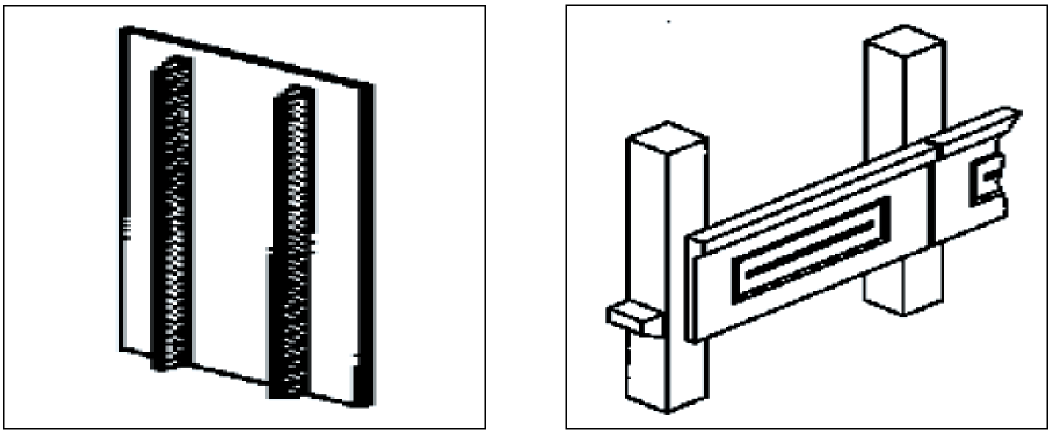
(a) Flat, hollow-core, or insulated panel

(b) Vertical window or mullion panel



(c) Horizontal window or mullion panel

(d) Ribbed Panel



(e) Double-tee panel

(f) Spandrel

Figure 1.2: Various types of architectural load-bearing wall panels. (Freeman, 1999)

1.3 Precast Sandwich Panel

Precast sandwich panel is a layered structural system composed of low density core material which acts integrally with the high strength facing material. Structures made of precast sandwich panels can be remarkably strong and lighter in weight. The trend for “stronger-lighter” product is becoming increasingly important in the construction industry.

Various forms of sandwich construction may be obtained by combining different wythe and core or insulation materials. The wythes may be constructed out of varieties of materials such as concrete, steel, aluminium, or carbon fiber material (Lee and Pessiki, 2006, Benayoune *et al*., 2006, Liew and Sohel, 2009, Jeom *et al*., 1999, Rice *et al*., 2006). The core layers are often composed of lightweight concrete, fibre reinforced composite, balsa wood, foam, polymer foam and structural honeycomb material such a aluminium honeycomb concrete (Liew and Sohel, 2009, Jeom *et al.*, 1999, Stoll *et al.*, 2004, Scudamore and Cantwell, 2002). These materials can be combined to form composite panels which enable the optimum design to be produced for particular applications.

A typical concrete sandwich panel is shown in Figure 1.3. It consists of an insulation layer which is enclosed by inner and outer concrete wyhtes. The concrete wythes may be of a standard shape, such as a flat slab, hollow-core section or double tee. The wythes can be connected together using shear connectors through the insulation layer to promote composite action so that the system can be used as structural element. Figure 1.4 shows a typical 3-D view of sandwich panel with truss shaped shear connectors.

Structural sandwich panels provide the dual functions of transferring load and insulating the structure. They may be used solely for cladding, or they may act as beams, bearing walls, or shear walls. Interest in sandwich panels as load-bearing wall panels has been growing over the past few years because manufacturers are looking for more viable products and are pleased with their structural efficiency, insulation property, light weight and aesthetics values. Sandwich panels are similar to other precast concrete members with regard to design, detailing, manufacturing, handling, shipping and erection; however, because of the presence of insulation layer, they do exhibit some unique characteristics and behavior.

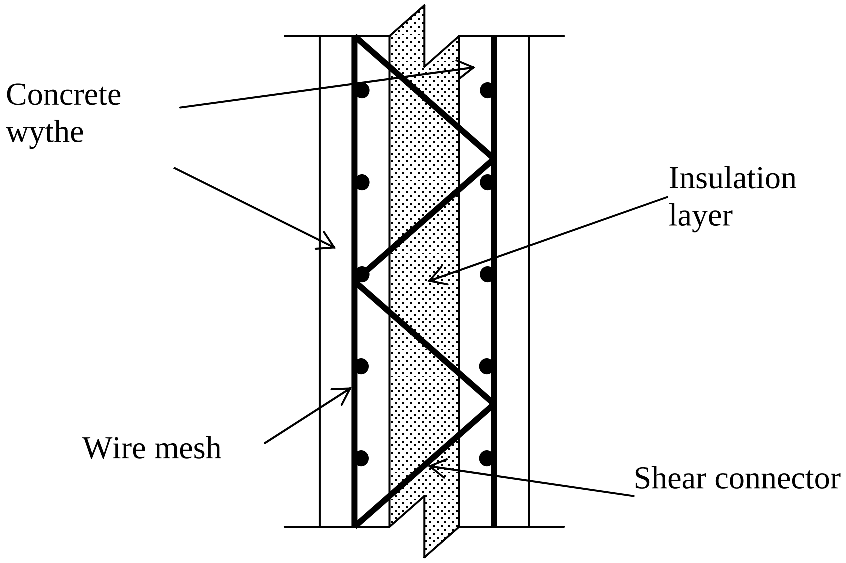


Figure 1.3: Typical Precast Concrete Sandwich Panel with Its Components

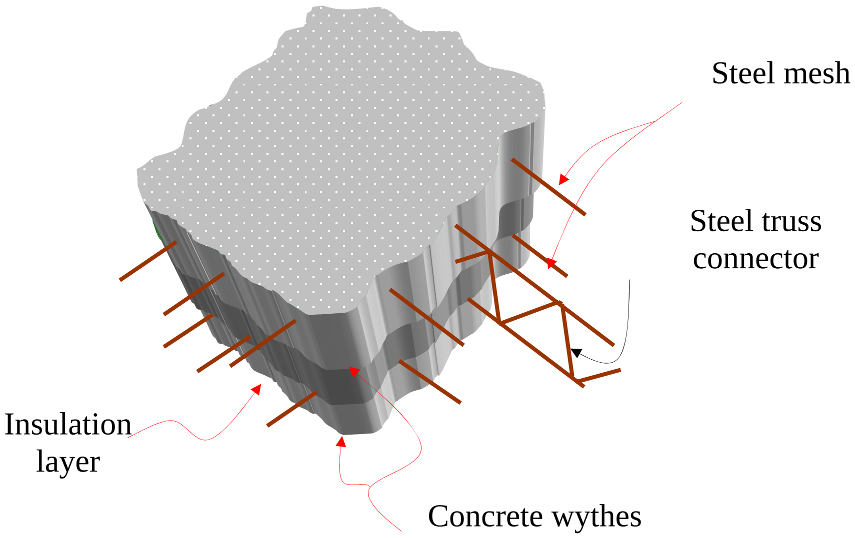


Figure 1.4: Precast Concrete Sandwich Panel in 3-D
(Benayoune *et al.*, 2006)

1.4 Lightweight Foamed Concrete

Foamed concrete has been widely used especially in the western countries. It is originated from Scandinavia some thirty years ago. Nowadays, foam concrete technology has been widely used in construction industries. It is considered as an attractive material for its lightweight, better thermal properties and ease of construction. In the United States for instance, foamed concrete are used in an increasing number of applications. Cast-in-place foamed concrete are used for insulating roof-deck systems and for engineered fills for geotechnical applications while precast auto-claved products are widely used as load-bearing blocks, reinforced wall, roof and floor units and as non load-bearing cladding panels over a primary structural frame (Tonyan and Gibson, 1992).

Foam concrete is a low density hardened Portland cement paste, containing a large number of small bubbles. Cement foam can be manufactured either by a chemical or a mechanical foaming process. In the chemical process, a powdered metal (usually aluminum) is added to slurry composed of cement and lime. Most of the aerated concrete produce with this method have densities between 480 and 960 kg/m^3 (Tonyan and Gibson, 1992).

In a mechanical foaming process, foaming agent is added into the cement slurry either directly or in a form of perform foam. The presence of cement causes the material to be cohesive after the hydration of the cement. The entrapped air bubbles increases the volume and thereby reduces the densities of a concrete. This volume between the slurry and the foam determine the density of the foam concrete. The preform foam provides better control of density and foam cell structure. The foamed concrete’s materials and characteristic properties are described in the following sections. In both the chemical and mechanical processes described above, the cement foam is usually cured in a moist environment at ambient temperature.

1.4.1 Materials

Foam concrete is a mixture of cement, fine sand, water and special foam, which produces a strong, lightweight concrete containing millions of evenly distributed and consistently sized air bubbles or cells. The density of foam concrete is determined by the amount of foam added to the basic cement, sand and the water mixed together.

1.4.2 Characteristic properties of foamed concrete

The characteristic properties of foamed concrete includes its compressive strength, tensile strength, shear strength, shrinkage, coefficient of linear expansion, acoustic and thermal insulation, and fire resistance. The characteristic properties of foamed concrete will be presented in the following paragraphs according to the report on Foamed Concrete Composition and Properties (British Cement Association, 1994).

The compressive strength of foam concrete is influenced by many features like density, age, moisture content, and the physical and chemical characteristics of its component materials and mix proportions. A relationship exists between the density and the strength where it is found that the higher the density of the mixture, the greater the strength of the end product. For foamed concrete with densities ranging from 300 to 1600 kg/m^3, the compressive strength at 28 days is from 0.2 to 12 N/mm^2. The compressive strength will continue to increase indefinitely due to the reaction with carbon dioxide, CO_2, present in the surrounding air.

Depending on the method of curing, the tensile strength of foam concrete can be as high as 0.25 of its compressive strength with a strain around 0.1% at the time of rupture. Meanwhile, the shear strength varies between 6% and 10% of the compressive strength.

Shrinkage property in foamed concrete is a phenomenon during the setting stage. The amount of shrinkage is dependent on the type of cement used, type of curing, the size and quality of the sand, the amount of cement in the mix, density of the concrete, and the water cement ratio. The greater extent of shrinkage occurs during the first 28 days of the concrete’s age.

The coefficient of linear thermal expansion for foam concrete is of the same order as that of normal concrete. Foam concrete has high sound absorption capacity and a very low transmission of heat. It is also extremely fire resistant where the level of resistance is greatly superior to normal concrete.

1.4.3 Advantages of Foamed Concrete

Foamed concrete has many advantages. However, the most important are its compressive strength and its low density. Foamed concrete in general has good mechanical strength combined with lightweight and low thermal conductivity. Good thermal insulation properties give energy conservation advantages which reduce the operating cost. Besides, it can be produced in a wide range of densities and properties that can suit any particular requirements. Like normal concrete, it can easily be mould to any desired shapes or sizes.

Foamed concrete is also an economical solution, particularly in large volume applications. It is self-compacting; as such, the casting process is much easier. Due to its lighter weight, lower crane capacity is required and lesser number in manpower is needed during the erection process. Its rapid installation contributes to the total cost saving. Placement of foamed concrete is a continuous operation from the mobile central plant where it pumps easily with relatively low pressure. The maintenance cost is also low because of its durability. It is also fire resistant and its surface texture makes it a good sound absorbent.

1.5 Precast Lightweight Foamed Concrete Sandwich Panel, PLFP

Lightweight foamed concrete can be produced by mixing sand, cement, water and stable foam using a mechanical air-entraining admixture. The product is a cementitious paste of cement and fine sand with micro discrete air cells uniformly distributed throughout the mixture to create a lightweight concrete. The density of the foamed concrete is controlled by the amount of tiny air pockets added into the mixture via foaming process. Lightweight foamed concrete has been used in construction for non-structural building wall panels or as partitions. It is considered as an attractive material because of its lightweight, better thermal properties and ease of construction.

Lightweight foamed concrete mixture can be designed to have higher strength which is close to the strength of the normal concrete. In order for lightweight concrete to be used as structural element, it must have the density of 1440 to 1840 kg/m^3. Higher density results with higher strength of concrete. For structural application, the concrete strength should be 17 MPa or above (American Concrete Institute, 1989).

Precast Lightweight Foamed Concrete Sandwich Panel or PLFP is proposed in this study as an alternative structural sandwich component that can meet the rapid housing demand in this country. It consists of lightweight foamed concrete as the wythes which enclose the polystyrene which act as the insulation layer. Shear connectors are embedded across each layer to allow load shearing between wythes. The strength and stability of the PLFP rely a lot on the stiffness of these shear connectors and its ability to transfer load between wythes. The primary use of structural lightweight concrete is to reduce the dead load of a building. Structural lightweight concrete provides a most efficient strength-to-weight ratio in structural elements. Reduction of weight will result in easy construction, reduction of transportation cost and reduced of foundations, which eventually will reduce the overall cost.

1.6 Problem Statement

The demands from the growing population and migration of people to urban areas require this country to look for alternative construction method to provide fast and affordable quality housing to its citizens. Efforts have been taken to move from the traditional building construction technique to a more innovative construction method to meet these demands. As a part of this effort, an extensive investigation to develope a Precast Lightweight Foamed Concrete Sandwich Panel or PLFP as a load bearing wall system is undertaken.

1.7 Objectives

The aim of this study is to develope a load-bearing Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) for use as structural component in low rise building construction. In order to achieve this aim, several objectives are set out:

1. To develop and construct the sandwich PLFP panel using the lightweight foamed concrete.

2. To propose the right mixture for lightweight foamed concrete of sufficient strength and density suitable for use as structural component.

3. To study the structural behaviour of the proposed sandwich PLFP panel by means of experimental work and finite element method, FEM.

4. To develop a semi-empirical expression to estimate the load carrying capacity of the PLFP panel.

1.8 Scope of Work

In order to develope and construct the sandwich PLFP panel using lightweight foamed concrete, an experimental programme which includes fourteen full-scaled specimens was conducted to study its behaviour and axial load carrying capacity. Finite element study was further conducted to examine the effect of various parameters which dictate the panel's strength and behaviour.

The experimental work started out with the pilot testing which includes trial mixing of lightweight foamed concrete to get the suitable density for the targeted compressive strength. The process of mixing was based on the typical mixture details for foamed concrete as given in British Cement Association. From the trial mixtures and the mixtures during the pilot testing and experimental programme, the right mixture for lightweight foamed concrete of sufficient strength and suitable density for use as a structural component is proposed.

The fourteen PLFP specimens in the experimental programme were tested under axial load to investigate its structural behaviour. The results were 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 in the FEM simulations 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 was used to study the efficiency and role of the shear connectors in transferring loads and to evaluate the extent of composite action achieved.

The results from the proposed FEM model and from the experimental work were analysed and compared. A semi-empirical expression was proposed to estimate the load carrying capacity of the PLFP panel. It was validated on the basis of the test data made available by previous research works.

1.9 Thesis Layout

The thesis consists of seven (7) chapters. The content of each chapter is described below:

Chapter I

This chapter presents an introduction of the Precast Lightweight Foamed Concrete Sandwich Panel, or PLFP, as an alternative building system which meets the challenge in the construction industry in Malaysia today. This chapter also discusses the objectives and the scope of work of the research.

Chapter II

This chapter presents the relevant literature review on the structural performance of the PLFP as sandwich wall panel. It also contains a review of the studies on lightweight foamed concrete and its properties. An overview of previous research works on sandwich wall panel of different material is also discussed with critical comments.

Chapter III

This chapter presents the methodology of the research, including the details on the actual and preliminary experimental work carried out to achieve the objectives as defined earlier. Fabrications and construction details of the test specimens and the materials used together with the test set up are described.

Chapter IV

This chapter contains presentation of results from the test data obtained from axial load tests on PLFP conducted experimentally in the present study. The observations are related to axial load bearing capacity, cracking patterns and mode of failure, load-deformation profiles, load-strain curves, and strain distribution across the panel’s thickness. The observations were made to verify the FEM model and facilitate interpretation of the theoretical results as described in Chapter V and Chapter VI.

Chapter V

This chapter describes the modeling and type of analysis used in the non-linear finite element study. It also presents the response of PLFP under axial load as determined by the FEM model. The applicability of the adopted FEM model was first validated on the basis of axial test data presented in Chapter IV. The results from the FE analysis are used in discussing the achievement of objectives and further drawing conclusions on the behaviour of PLFP panels as load-bearing wall element.

Chapter VI

This chapter presents the discussion of the results obtained from the experimental work and FEM. A semi-empirical expression is developed to estimate the strength capacity of PLFP panels using conventional approach based on reinforced concrete principles and data from previous research.

Chapter VII

A summary of the major findings of the study together with some recommendations for further work is given in this chapter.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Precast concrete sandwich panel or PCSP technology has advanced gradually over the past four decades in North America. The first prefabricated panels were of non-composite type and consisted of a thick structural wythe, a layer of insulation and a non-structural wythe (Seeber *et al.*, 1997). PCSP have all of the desirable characteristics of a normal precast concrete panel such as durability, economy, fire resistance, large vertical spaces between supports, and potential usage as shear walls, bearing walls, and retaining walls. On top of that, PCSP can be relocated to accommodate building expansion. The hard surface on both the inside and outside of the panel provides resistance to damage and a finished product requiring no further treatment.

Many alternative forms of sandwich panels may be obtained by combining different facing and core materials as discussed previously in the second paragraph of Section 1.3 in Chapter 1. The combined materials can form composite panels which allow optimum design for various applications. The good properties of individual materials can be combined and the bad ones eliminated. It takes advantage of the shear strength of a lighter core material and the high compressive and tensile strength of high densed wythes to obtain higher strength to weight ratios. The core material separates and stabilizes the outer facings against buckling under edgewise compression, torsion or bending. The wyhtes are usually made of high-strength material and they carried the primary loads. They resist tension and compression to prevent buckling under compression, tension failure and impact deformation.

Generally there are three types of pre-cast concrete sandwich panels or PCSP depending on the degree of composite action achieved (Shutt, 1997). A non-composite sandwich panel is one in which each concrete wyhte acts independently to resist bending. Plane section behaviour is obtained in each wythe, but not through the entire panel depth. A fully composite sandwich panel is one in which the two concrete wythes act integrally to resist bending allowing the entire panel to perform as a single unit. In theory, a fully composite panel exhibits plane section behaviour throughout its entire depth at all locations along its span. Full composite behaviour is achieved by providing sufficient horizontal shear transfer between the wythes. Shear connectors were tied to the steel mesh in the concrete wythes. The connectors function to transfer load from the outer concrete wythe to the inner one.

A partially composite sandwich panel is one in which concrete wyhtes act atleast partly together to resist bending. Thus, a partially composite panel resists bending to a degree between that of a fully composite panel and a non-composite panel. The degree of composite action exhibit by a panel may change throughout the loading history of the panel. The distribution of stress and strain for the three types of sandwich wall panel is shown in Figure 2.1.

A fully composite panel fails either by concrete crushing or steel reinforcement yielding without failure of the connectors. The fully composite action is reflected in strains remaining essentially linear across the panel thickness, as shown in Figure 2.1(a). A PCSP is considered to be non-composite if its concrete wythes are tied with connectors that do not have the capacity for longitudinal shear transfer. In this case, the two wythes act independently. The variation of strains across the thickness, in case of non-composite panels is shown in Figure 2.1(c). A PCSP is considered partially composite if its connectors can transfer only a fraction of the longitudinal shear as required for the fully composite action. In this case, the connectors fail before concrete crushing or yielding of the reinforcement. Figure 2.1(b) describes the variation of strain across the panel thickness in such a case.

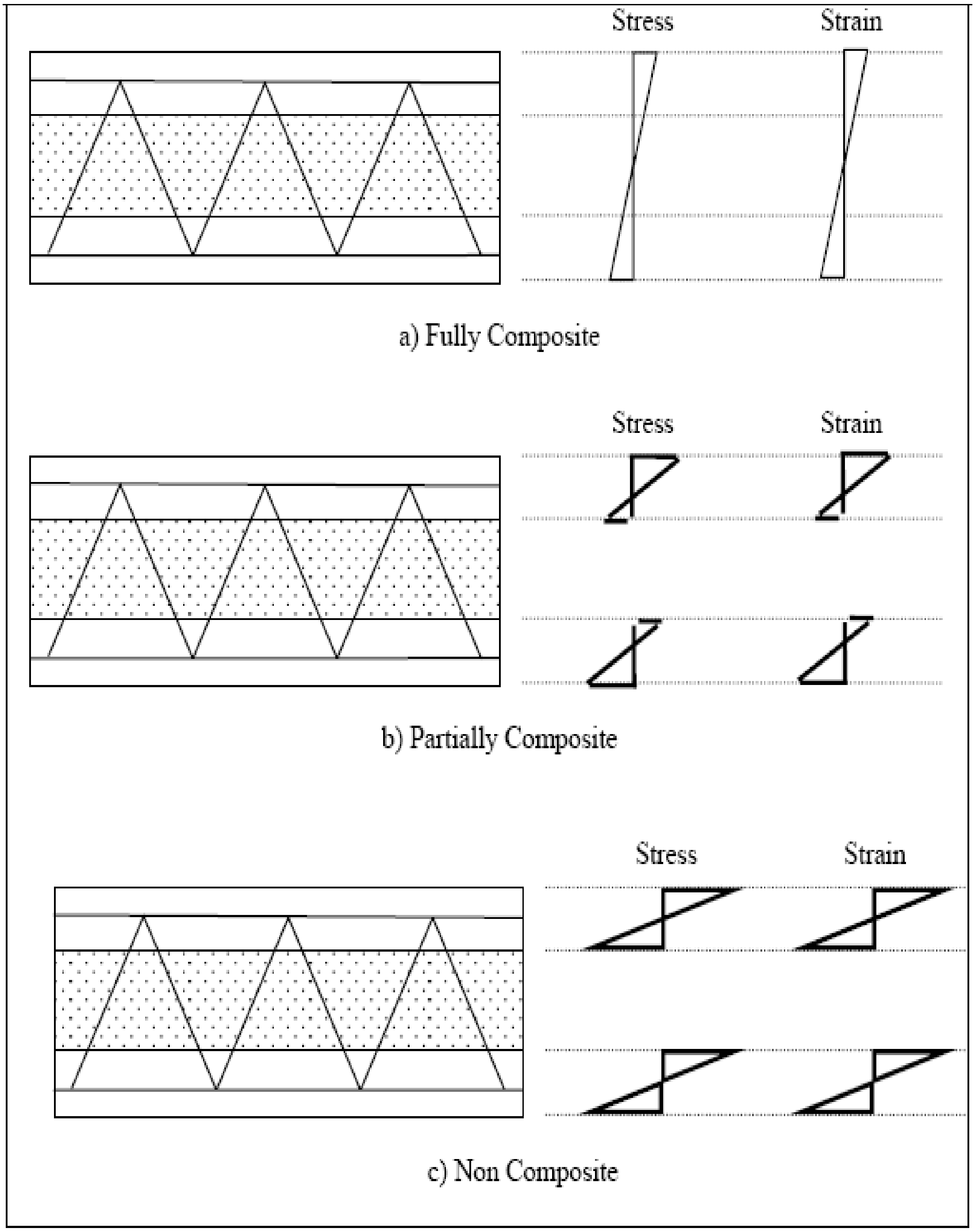


Figure 2.1: Types of Compositeness of pre-cast concrete sandwich panel. (Shutt, 1997)

Sandwich panels have gained much attention as an effective structural element in engineering field. It has been used as load-bearing members in naval structures (Aicher and Hofflin, 1999). However, in the building and construction industry, most of the research published on sandwich panels are related to the study of the non-load bearing non-composite type of PCSP (Jokela *et al*., 1981, Olin *et al*., 1984, Hopp *et al*., 1986 and Bush, 1998). Section 2.2 in this Chapter will discuss in details the previous research that has been carried out on sandwich panels. The section will be narrowed down to several sub-sections which will discuss the various material used as the wyhte and core, the shear connectors influences on the behaviour of panels and the structural behaviour of panels under various loading that have been done on this type of panel especially in the context of their applications as load bearing walls.

2.2 Review of Past Studies on Sandwich Panel

Previous research on sandwich panel have shown that various materials could be used as the core layer and skin faces. Therefore, a sandwich panel is unique in its own way because the materials it uses are different from any other sandwich panel. Sandwich panel development had started with normal weight material as both core and faces. However, the use of lightweight material as core layer has become more familiar in recent years as will be discussed in the next paragraphs. Review of the previous studies on the materials used, shear connector's effect on the structural behaviour, its structural behaviour, lightweight sandwich panel and the lightweight foamed concrete are presented in the sections below. All these sub-topics are actually interrelated. For instance, the materials and shear connectors used seem to have significant effects on the structural behaviour of the sandwich panel whilst the structural behaviour of the sandwich panel influences the types of materials chosen.

2.2.1 Materials

The wythes of sandwich panels are generally made of thin, high strength sheets material. The structural requirements for wythe materials are their abilities to resist local loads and resistance to corrosion and fire. The core materials are generally thicker and made of lower densed materials. The core is low in density because the core usually does not take any load and function as an insulation material. As stated previously, many alternative forms of materials may be used either as the wythes or as a core layer of the sandwich panels. Various types of materials therefore provide various structural behaviours of the sandwich panels.

Jeom *et al.* (1999) investigated the strength characteristics of aluminum sandwich panels with aluminum honeycomb core theoretically and experimentally (Figure 2.2). They found out that the sandwich structure offers advantage in term of lighter weight for design of weight critical structures. It is also observed that aluminum honeycomb core has excellent properties with regard to weight savings and fabrication costs.

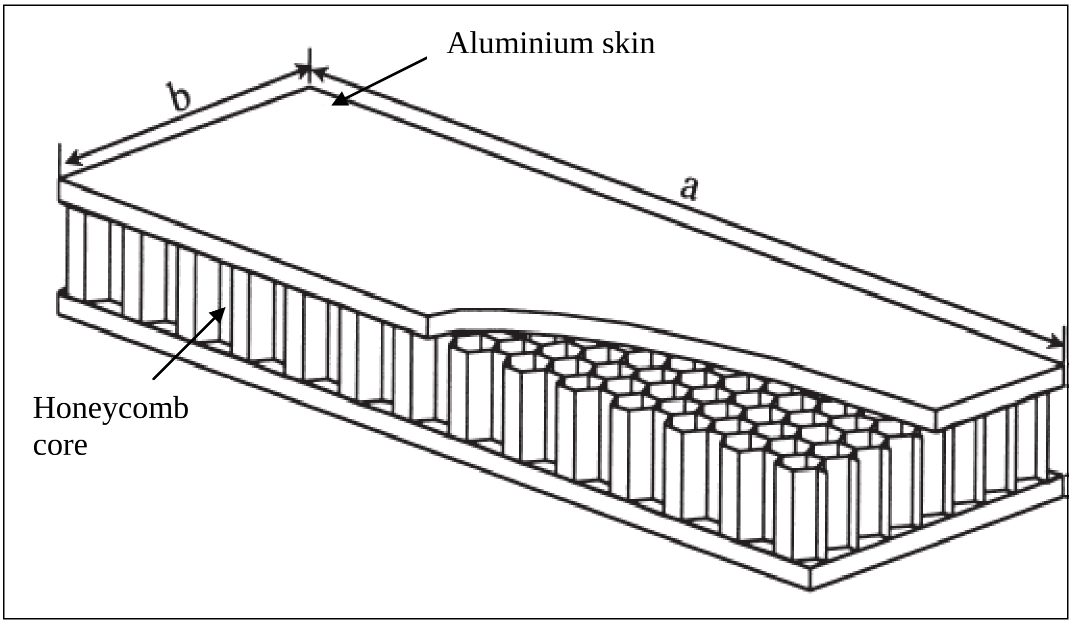


Figure 2.2: Honeycomb-cored sandwich panel (Jeom *et al.*, 1999)

Stoll *et al*., (2004) investigated the effect of weight, strength, stiffness and failure mode of Fiber-Reinforced Composite (FRC) core in composite sandwich construction. In this study, dry fiber and preform foam are used in the molding processes to produce a fiber reinforced composite core panel. An FRC core pre-form was manufactured by cutting a foam board strip which was wrapped by fiber glass fabric around it as shown in Figure 2.3 and consolidating multiple wound strips into sheets as in Figure 2.4. Fiber glass fabric is added to the surfaces of the pre-form and the lay-up is infused with thermoset resin to produce a molded panel as shown in Figure 2.5. The fiberglass used in FRC test panel is E-glass fabric with G6 and G18 facing design. To enable comparisons of FRC cores with other core materials, test panels with 2.5 cm thick foam and balsa cores were molded. An 80 kg/m^3 PVC foam test panel was molded with the same facing design as the G6 test panels, and a nominal 150 kg/m^3 balsa was molded with the same facing design as the G18 test panels. The results of shear strength, stiffness and compressive strength on the FRC core were compared with the results taken from the tests on panels with PVC foam and balsa cores. It is found that the use of FRC cores increased the shear and compressive strength with only minor increase in core density (Table 2.1).

Figure 2.3: Foam board strip wrapped by fiber glass fabric (Stoll *et al*., 2004)

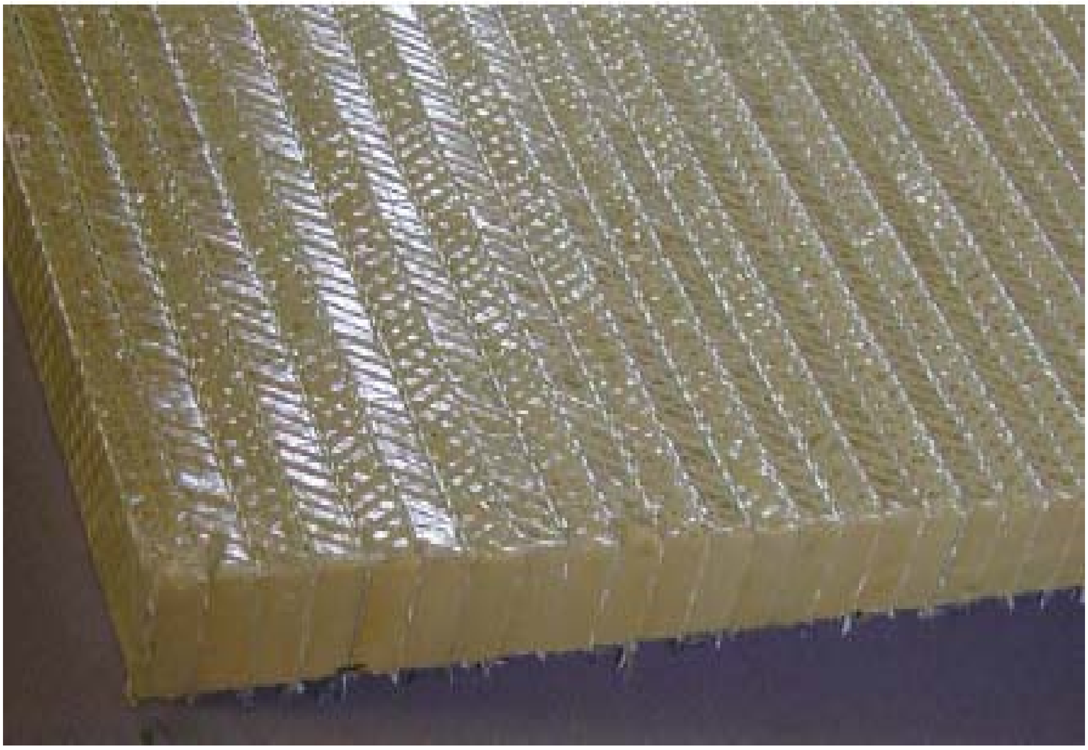


Figure 2.4: Core Preform (Stoll *et al*., 2004)

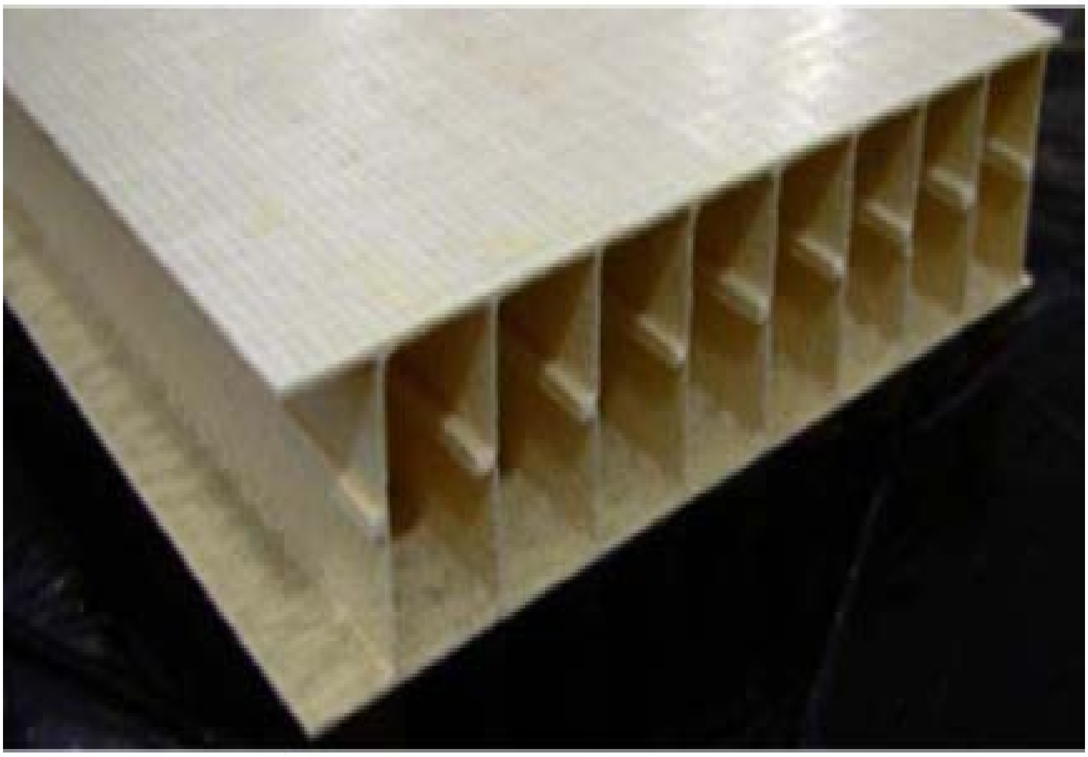


Figure 2.5: Molded panel with foam removed, showing composite webs and resin ridge (Stoll *et al*., 2004)

Table 2.1: Measured Properties for FRC, PVC foam and Balsa Cores.

(Stoll *et al.*, 2004)

Core design	Infused core density kg/m^3 (lb/ft^3)	Shear strength, short-beam bending MPa (psi)		Shear strength, plate shear MPa (psi)		Shear modulus MPa (ksi)		Compressive strength MPa (psi)	Tensile strength MPa (psi)
		L	W	L	W	L	W		
G6	97 (6.0)	1.52 (221)	0.11 (16)	1.80 (261)	0.18 (26)	134 (19.4)	5.5 (0.8)	2.83 (410)	0.82 (119)
G18	103 (6.4)	3.79 (549)	0.20 (28.5)	3.09 (448)	0.23 (34)	257 (37.5)	6.2 (0.9)	7.55 (1095)	2.17 (314)
PVC foam	76 (4.8)	1.08 (157)		0.87 (126)		28 (4)		1.14 (166)	2.15 (312)
Balsa	348 (21.7)	2.35 (341)		2.57 (373)		276 (40)		11.64 (1690)	9.50 (1380)

Lee *et al.* (2006) in their paper described an ongoing project to demonstrate an affordable, safe, and energy-efficient housing technology based on expanded polystyrene (EPS) foam panels with a cementitious coating. In this system, the EPS was acting as the core while the cellulose fiber cement board panel was acting as the facings of the panel. The EPS core layer was embedded with the wire trusses which were connected to the wire mesh that enclosed the EPS layer. The cement board facings were screwed to the surface of the EPS layer. The concepts being described are as shown in Figure 2.6, Figure 2.7 and Figure 2.8. Preliminary tests were conducted to analyze the costs, to simulate seismic forces, to conduct the test against environmental conditions, and to build pilot houses.

The test results indicate that houses constructed from EPS structural insulated panels with a cementitious coating meet the defined needs of populations in many parts of the developing world. The structural and fire safety test, energy use and cost analysis showed that panel homes met the necessary criteria of safety and affordability. Structural simulations demonstrated that the technology was highly resistant to ordinary and extreme forces such as high wind, snow load, and earthquakes. The panel homes were also shown to be safe in fire and damages was easy and inexpensive to repair. Affordable concerns in this research were addressed through the cost analysis and energy modeling, which demonstrated that the panel design is inexpensive to build and maintain.

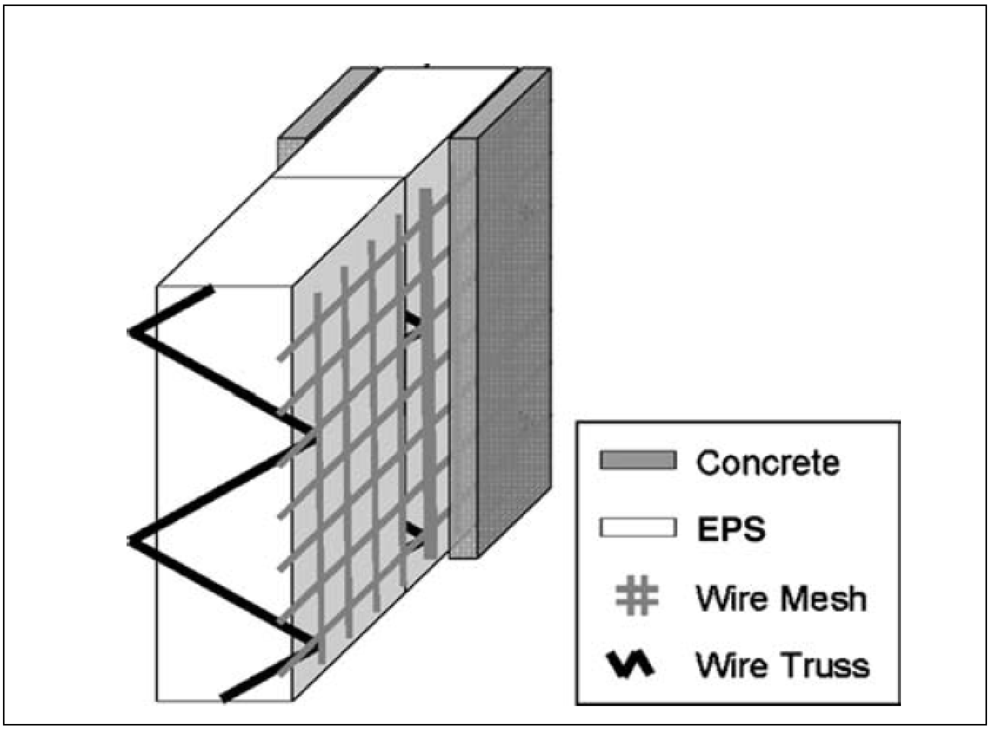


Figure 2.6: EPS Embedded With Trusses (Lee *et al*., 2006)

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