STRUCTURAL BEHAVIOUR OF PRECAST CONCRETE SANDWICH PANEL USING RECYCLED AGGREGATE CONCRETE UNDER TRANSVERSE LOAD

HAMZA MASAUD AL. MABROUK KHALIFA

A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Civil Engineering

Faculty of Civil and Environmental Engineering
Universiti Tun Husseion Onn Malaysia

JUN 2013

ABSTRAK

Kajian terdahulu memberi penekanan terhadap pencarian bahan alternatif dalam sistem bangunan komposit untuk menghasilkan bangunana yang mesra alam, mengunakan kos bahan yang rendah dan kuat untuk diaplikasikan dalam industri pembinaan. Dalam kajian ini, batu baur kitar semula,(RA) telah digunakan untuk menggantikan batu baur semula jadi. Kajian ini membentangkan daya ketahanan RA dengan nisbah yang berbeza daripada 25, 50, 75 dan 100 peratus Panel Struktur Apit dari konkrit kitar semula, (RACSP). Kelakuan panel RACSP itu diuji kaji dan dianalisis dalam konteks kapasiti beban melintang, profil beban-pesongan, pengedaran penegangan, corak keretakan dan bentuk kegagalan. LVDT digunakan untuk mengukur pesongan ditengah panel dan slip antara kedua-dua konkrit apit(wythes) daripada RACSP. Tolok tekanan digunakan untuk mengukur tekanan pada permukaan apit konkrit. Didapati bahawa kekuatan panel RA menurun secara tidak bekadar terus dengan peningkatan peratusan RA dalam konkrit. Panel kawalan dengan NA menunjukkan nilai beban maksimum deperolehi lebih tinggi berbanding panel dengan konkrit kitar semula. Peratusan pengurangan beban maksimum panel dengan RA adalah dalam 15 peratus bagi peningkatan peratusan RA manakala pengurangan 31 peratus berbanding dengan panel kawalan. Didapati bahawa semua panel akhirnya gagal disebabkan oleh ketegangan keluli. Ia menunjukkan bahawa retak pertama berlaku pada kira-kira 48-67 peratus daripada kegagalan beban. Pengaruh RA dan kesan beban melintang pada kekuatan maksimum RACSP telah dibincangkan. Keretakan pada permukaan konkrit diperhatikan pada kedua-dua apit konkrit.

ABSTRACT

Previous studies have been focusing on finding alternative materials in a composite building system in order to provide a strong, environmental friendly, low cost material to be used in the construction industry. In this research, recycle aggregate, RA, has been used instead of natural aggregate. This study presents the viability of RA with different ratios of 25, 50, 75 and 100% in Recycled Aggregate Concrete Sandwich Panel, RACSP. The structural behavior of the RACSP was investigated experimentally and analysed in the context of transverse load capacity, load-deflection profile, load strain curves, cracking patterns and mode of failure. LVDT was used to measure the mid-span deflection and the slip between both wythes of RACSP. Strain gauges were used to measure the strain on the surface of concrete wythes. It was found that the strength of the panels with RA decreased nonlinearly with the increase of percentage replacement of RA in concrete. Control Panel with NA showed the highest value of ultimate load in comparison with others. The percentage of reduction in the ultimate load of panels with RA was about 15% for an increase the replacement percentage of RA whereas the maximization in the ultimate load was about 31% in comparison with Control Panel. It was observed that all the slab ultimately failed by tension steel failure. It was noticed that the first crack occurred at about 48-67% of the failure load. Influence of the RA and the impact of transverse load on the ultimate strength of RACSP specimens have been discussed. Cracks were observed in both wythes.

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AAC - Autoclaved Aerated Concrete
A_s - Area of of tension reinforcement
B,b - width of panel section
D, d - Diameter
E_c - Modulus young of concrete
EI - Elastic STIFFNESS
EPS - Expended polystyrene insulation
E_s - Modulus young of steel
F_c - Compressive force in concrete
f_{cu} - Compressive strength of concrete
FEM - Finite element models
FRP - Fiber Reinforced Polymer
FRPBB - Fiber reinforced plastic bent bar
F_T - Force in tension reinforcement
f_y - Yield strength of steel
H, h - High of panel
H/B - Aspect ratio of panel
H/t - Slenderness ratios of panel
l - The panel span
LVDT - Linear Voltage Displacement Transducers
M_u - Ultimate bending moment
NA - Natural aggregate
NC - Normal concrete
PCSP - Precast concrete sandwich panel
P_u - Ultimate flexural load
RA - Recycled aggregate

RAC - Recycled aggregate concrete

RACSP - Precast recycled aggregate concrete sandwich panel

S - Strain gauge

T - Splitting tensile strength

t - Thickness of Panel

t_1 - Thickness of core layer

t_2 - Thickness of wythe

UTHM - Universiti Tun Hussein Onn Malaysia

UTM - Universiti Teknologi Malaysia

w - Wide of panel

ASTM - American Standard Testing Method

LIST OF APPENDICES

TABLE OFCONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

Precast concrete components are widely used throughout the world, primarily in the building sector. The rapid growth of the building industry in the last several years and the increasing demand for high quality structures necessitates a building industry that can continuously seek improvement, leading to a more sophisticated industrialization. The advent of new industrial methods has shown that mass production of precast concrete components has increased the quality as well as reduced the cost of production.

Cost is reduced due to lesser construction time and amount of needed labor. Precast concrete is defined as concrete which is cast in some location other than its position in the finished structure. One of the building elements in a precast building system is precast concrete sandwich wall panel (PCSP). The difference between precast concrete wall panels and precast concrete sandwich wall panels is the presence of an intervening layer of insulation**.**

1.2 Precast Concrete Sandwich Panel

Interest in precast concrete sandwich panel has grown in the past few years because manufacturers are looking for new and more efficient products. Architects and engineers are pleased with the energy performance and general aesthetics of the panels and contractors have found that the use of sandwich panels allow their project sites to be cleaner and easier to manage (J. M. Davies, 1997).

PCSP's consist of a single layer of insulation sandwiched between two precast concrete layers. The two layers of precast concrete are interconnected by a series of shear connectors, concrete webs or a combination of the two. The thickness of each layer depends on the function of the panel. Based on the application of the panels, they can be categorized as non-composite, partial composite or full composite. The non-composite panel refers to the panels with two concrete layers acting independently when load is applied. The connectors have no capacity for longitudinal shear transfer. Normally, the two concrete layers have different thicknesses. The thicker layer resists the applied load and acts as the structural layer.

In the PCI Committee Report, it was mentioned that experience showed that early bond between certain insulation types and the concrete layers provide shear transfer for composite action during handling, but the bond is considered unreliable for the long term. The shear connectors can transfer between 0 to 100 percent of the longitudinal shear required for a composite panel (PCI Committee, 1997). The composite or fully composited panels refer to panels with two concrete layers acting as one unit when load is applied. This is accomplished by providing full shear transfer between the two layers. This type of panel may be used as load bearing structural panels.

1.3 Recycled Aggregate Concrete

Demolition of old and deteriorated buildings and traffic infrastructure, and their substitution with new ones, is a frequent phenomenon today in a large part of the developing world. The primary reasons for this situation are: a change of purpose for buildings, structural deterioration, rearrangement of a city, expansion of traffic directions and increasing traffic load, and natural disasters (earthquake, fire and flood), . For example, about 850 million tons of construction and demolition waste are generated in the European Union per year, which represent 31% of the total waste generation (Fisher & Werge, 2009). In the USA, the construction waste produced from building demolition alone is estimated to be 123 million tons per year (Federal Highway Administration, 2004). The most common method of managing this material has been through its disposal in landfills. In this way, huge deposits of construction waste are created, consequently becoming a special problem of human environment pollution. For this reason, in developed countries, laws have been established to restrict this waste in the form of prohibitions or special taxes for creating waste areas.

As production and utilization of concrete rapidly increases, there is a concurrent increased consumption of natural aggregate as the largest concrete component. For example, two billion tons of aggregate are produced each year in the United States. Production is expected to increase to more than 2.5 billion tons per year by the year 2020. This situation leads to a question about the preservation of natural aggregates sources; many European countries have placed taxes on the use of virgin aggregates. A possible solution to these problems is to recycle demolished concrete to produce alternative aggregates for new structural concrete. Recycled concrete aggregate (RAC) is generally produced by a two-stage crushing of demolished concrete, and screening and removal of contaminants such as reinforcement, paper, wood, plastics and gypsum. Concrete made with such recycled concrete aggregate is called recycled aggregate concrete (Transportation Applications of Recycled Concrete Aggregate, 2004).

1.4 Problem Statement

The pace of development in Malaysia has spurred the demand for fast, cost-effective and comfort residential building, the current construction method is to use conventional concrete.

However, the use of conventional concrete has several disadvantages in terms of its large self weight, usage of natural resource aggregate and a higher cost of steel reinforcement. Therefore, an alternative composite method is urgently needed to provide a strong, environmental friendly, low cost material to be used in the construction industry.

1.5 Objective of Study

This research focuses on the behaviour of the precast recycled aggregate concrete sandwich slab panel (RACSP).

The objective keys are:

1. To propose a suitable design for sandwich panels by using recycled aggregate concrete (RAC).
2. To determine the load bearing capacity of the RACSP under flexural.
3. To determine the load deflection profile and strain distribution of the RACSP under flexural.
4. To compare the load bearing capacity of precast concrete sandwich panels using natural concrete NC with RACSP using recycled aggregate.

1.6 Scope of Study

This study is focused on an experiment in the lab. RACSP consist of two outer layers made of concrete with added recycled material as its aggregate. These two outer layers enclose an inner layer made of polystyrene. The panels are strengthened using BRC steel embedded in the outer layers and steel shear connectors tied to the reinforcement and embedded through the polystyrene layer.

During the experimental program, five sandwich panels have been prepared and designated by a name, i.e. PA-l to PA-5. The size of all the panels is kept constant at a height of 2000 mm, the thickness of outer layers at 40 mm, and a thickness of the polystyrene inner layer at 20 mm by a width of 750 mm.

Specimen PA-1 has been cast using natural concrete NC as the outer layers and it is used as the control panel. Specimens PA-2, PA-3, PA-4 and PA-5 were cast using RAC with a replacement percentage of RA (25%, 50%, 75% and 100%), respectively. The concrete wythe for all specimens used steel reinforcement with 6 mm BRC with 200 mm x 200 mm openings which were tied to 6 mm diameter mild steel trusses as single shear connectors. All panels were tested under flexural till failure.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Precast concrete sandwich panels have been in use for more than 40 years in North America. Prior to 1960, sandwich technology had been confined almost entirely in aerospace applications. The World War II Mosquito aircraft is often quoted as being the first major application of sandwich panels but there were numerous earlier, though less spectacular, uses of the sandwich principle. By 1960 increasing numbers of alternative uses were discovered: in building, refrigerated storage, automobile and shipbuilding industries. This period was also the beginning of a worldwide boom in prefabricated building elements for diverse applications (J. M. Davies, 1997).

It is generally believed that aggregate RA was first used in 1945 to rebuild concrete structures damaged in WWII. The high demand for concrete required new applications to meet that demand (Kheder & Al-Windawi, 2005). Factors like the depletion of natural aggregates, tightened environmental laws and waste disposal influenced the application of RAC.

2.2 Properties of Material

Precast concrete sandwich panels are made from numerous materials and many experiments have been carried out using different materials to identify precast concrete sandwich panels and their structural behaviour. These include***:*** foam concrete, steel, timber, insulation materials, and others.

2.2.1 Mixture Concrete with RAC

Recycled aggregate can be generated from demolished construction structures which are comprised of broken members or components such as the slab, beam or brick wall. One method of recycling is to crush these components using a steel hammer. It is then put into a jaw crusher where the construction debris is further broken down into required sizes. In order to provide crushed aggregate with acceptable quality, the demolished construction concrete can be crushed using primary and secondary crushers (Ismail A R., 2009).

The characteristics of recycled aggregates are suitable in the production of the structural concrete. Particularly worthy of mention is their lower density and higher water absorption level in comparison with natural aggregate because it contains the attached cement paste. The density of these recycled materials is about 3-10% lower and water absorption is about 3-5 times higher than the corresponding natural aggregates. The compressive strength of recycled concrete can be increased by the addition of silica fume. The elasticity of the concrete with recycled aggregate is low when compared to the concrete with natural aggregate (Belén & Fernando., 2001).

Recycled aggregate concrete can acquire sufficient quality as structural concrete through material design and by using material that conforms to all related quality expectations. Recycled aggregate concrete can also be designed by applying the value of a relative quality method. Therefore, it is considered applicable as aggregate for use in precast concrete products. Up to 30% of natural crushed coarse aggregate can be replaced with coarse recycled aggregate without significantly affecting any of the mechanical properties of the concrete. As replacement amounts increase, drying, shrinkage and creep will increase and tensile strength and modulus of elasticity will decrease. However, compressive strength is not significantly affected. It is recommended that recycled aggregate concrete be batched - pre-wetted and close to a saturated surface dry condition, like lightweight aggregates. To achieve the same workability, slump, and water-cement ratio, as in conventional concrete, the paste content or amount of water reducer generally has to be increased. Concrete with RCA can be transported, placed, and compacted in the same manner as conventional concrete (Farmington Hills & Michigan,. 2001).

Recycling concrete provides sustainability in several different ways. The simple act of recycling the concrete reduces the amount of material that must be land filled. The concrete itself becomes aggregate and any embedded metals can be removed and recycled as well. As space for landfills becomes premium, this not only helps reduce the need for landfills, but also reduces the economic impact of the project. Moreover, using recycled concrete aggregates reduces the need for virgin aggregates. This in turn reduces the environmental impact of the aggregate extraction process. By removing both the waste disposal and new material production needs, transportation requirements for the project are significantly reduced. In addition, recycled concrete aggregates absorb a large amount of carbon dioxide from the surrounding environment (Federal Highway Administration., 2004).

2.2.2 Polystyrene

Polystyrene foam begins with solid polystyrene crystals. The crystals, along with special additives and a blowing agent, are fed into an extruder. Within the extruder the mixture is combined and melted, under controlled conditions of high temperature and pressure, into a viscous plastic fluid. The hot, thick liquid is then forced in a continuous process through a die. As it emerges from the die it expands to foam, is shaped, cooled, and trimmed to dimension. Figure 2.1 shows the usage of polystyrene in a concrete sandwich panel (Karim S et al., 2012).

The key advantages of extruded polystyrene insulation are:

i. The consistent temperature on the inside will eliminate need for artificial cooling and heating.

ii. Regulated temperature passively created through the superior thermal mass forms a more pleasant inner environment.

iii. It saves costs on artificial temperature control devices such as air conditioning systems.

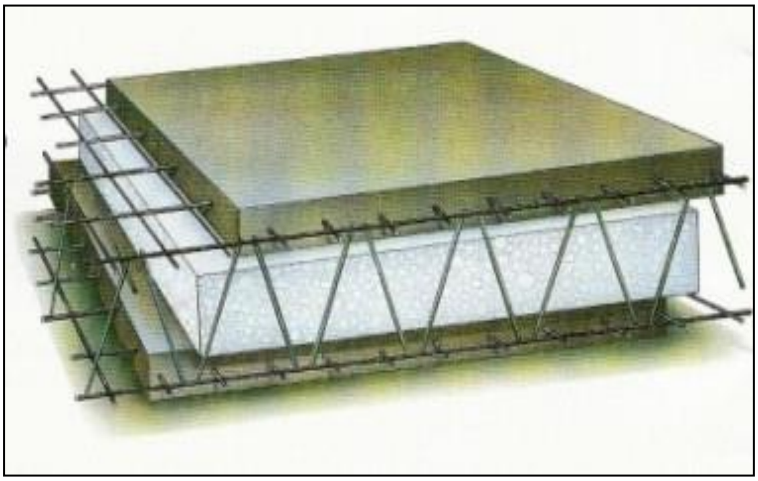


Figure 2.1: Usage polystyrene in sandwich panel

(Karim S et al, 2012)

2.2.3 Shear Connectors

In a report by the PCI it clearly explained the shear connector's properties and its function in precast sandwich wall panels. Shear connectors are used to transfer in-plane shear forces between the two wythes. Sandwich panels are usually designed as one-way structural elements; shear forces are generated due to longitudinal bending in the panels. In addition, the shear connectors may be used to transfer the weight of a nonstructural wythe to the structural wythe. Shear connectors that are designed to be stiff in one direction and flexible in another are called one-way shear connectors (PCI Committee, 2011).

Examples of these are longitudinal steel-wire trusses, solid ribs of concrete, flat sleeve anchors, fiber composite rectangles, and small-diameter bent bars as shown in Figure 2.2. Care must be taken in the manufacturing process to maintain the intended orientation of one-way connectors. Other shear connectors are stiff in at least two perpendicular directions and will consequently transfer both longitudinal and transverse horizontal shear. Examples of these are solid zones of concrete (often located at each end of the panel and at lifting points), connection plates, cylindrical sleeve anchors, and crown anchors. Connection plates and crown anchors are normally installed in solid zones of concrete and can therefore be considered rigid shear connections as shown in Figure 2.3.

Capacities of shear connectors may be obtained from the connector manufacturer or, in some cases, calculated using allowable bond stresses for plain smooth bars along with allowable steel stresses for bending, shear, and axial forces. When solid zones of concrete are utilized, a commonly used ultimate shear stress value is 80 psi (550 kPa) across the area of solid regions (ACI 318-05, 2005).

In some cases, the insulation layer itself may transfer shear between the wythes. Rough-faced, dense insulation provides more shear transfer than slick-faced insulation. Shear resistance that may be available from bonded insulation is, however, considered to be temporary. With non-composite panels, the assumption is sometimes made that the insulation provides sufficient shear transfer to create composite action during form stripping, handling, and erection, but the shear transfer is not relied on to provide composite action for resisting service loads. It should be noted that certain tension connectors might also provide some shear resistance. Use of panels with these connectors may be justified by providing data to the proper building officials (ACI 318-05, 2005).

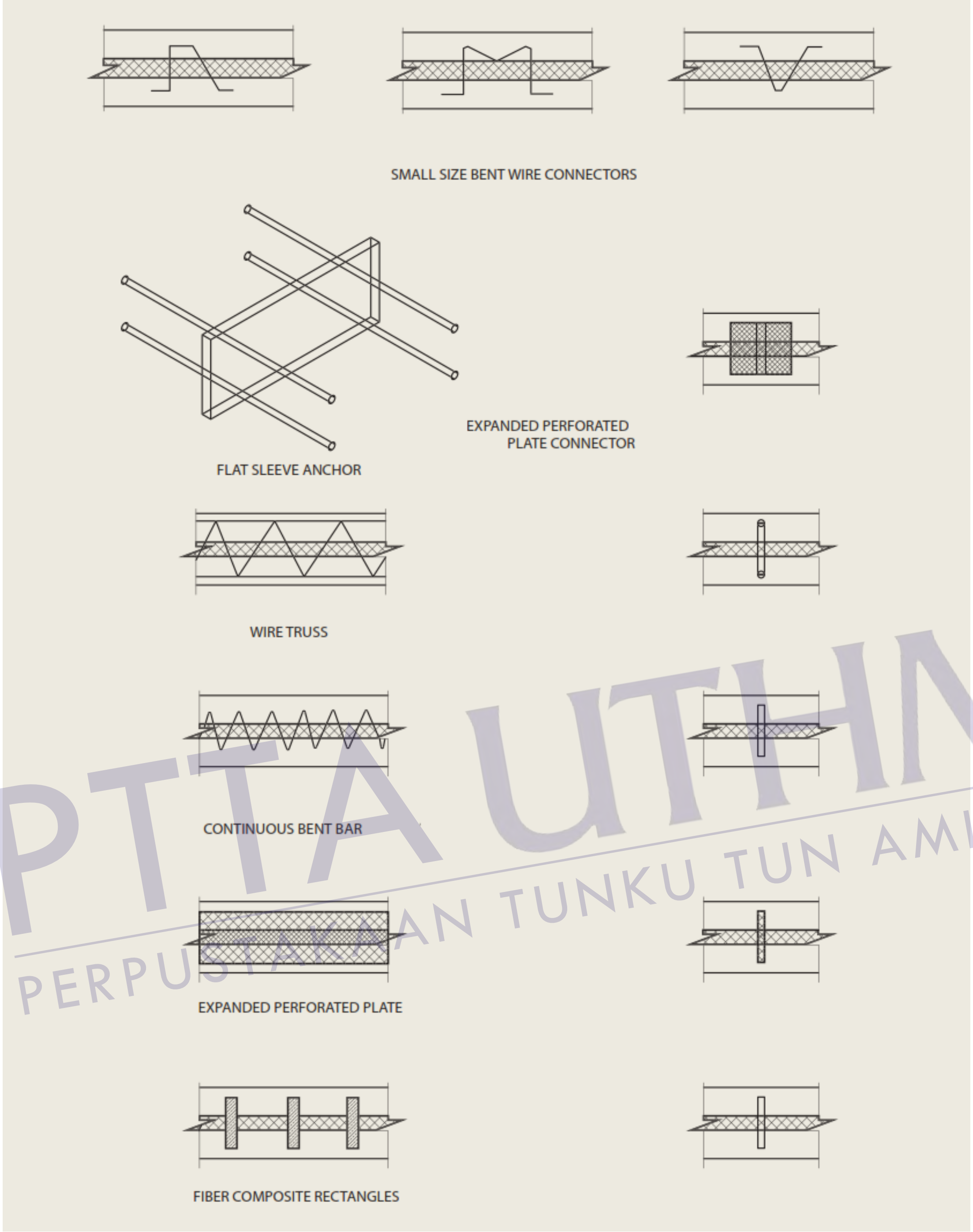


Figure 2.2: One-way shear connectors, stiff in only one direction.

(PCI Journal Spring 2011)

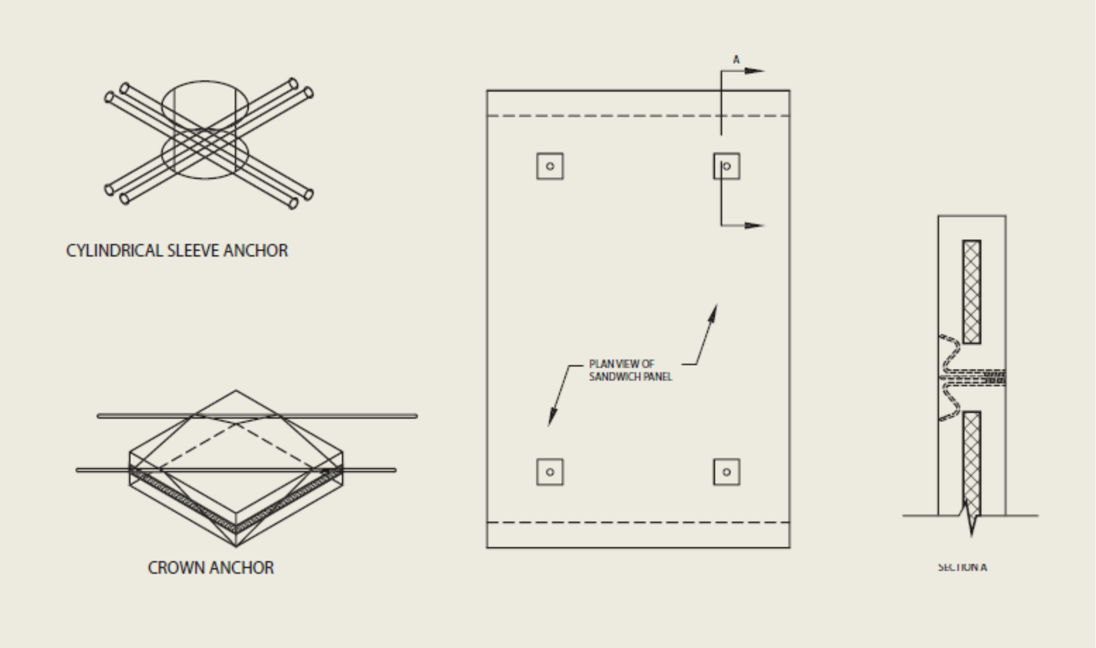


Figure 2.3: Two-way shear connectors, stiff in at least two perpendicular directions. (PCI Journal Spring 2011)

Non-composite connectors are generally considered capable of transferring only tension forces between the wythes. Shear connectors are used in non-composite panels to transfer normal forces between wythes and in composite panels as auxiliary connectors to the shear connectors when the spacing of the shear connectors is large. Because these connectors are unable to transfer significant shear, their contribution to composite action is usually neglected. Examples of tension connectors are plastic pins, fiber composite connectors, metal C-ties, M-ties, hairpins, and continuous welded ladders Figure 2.4.

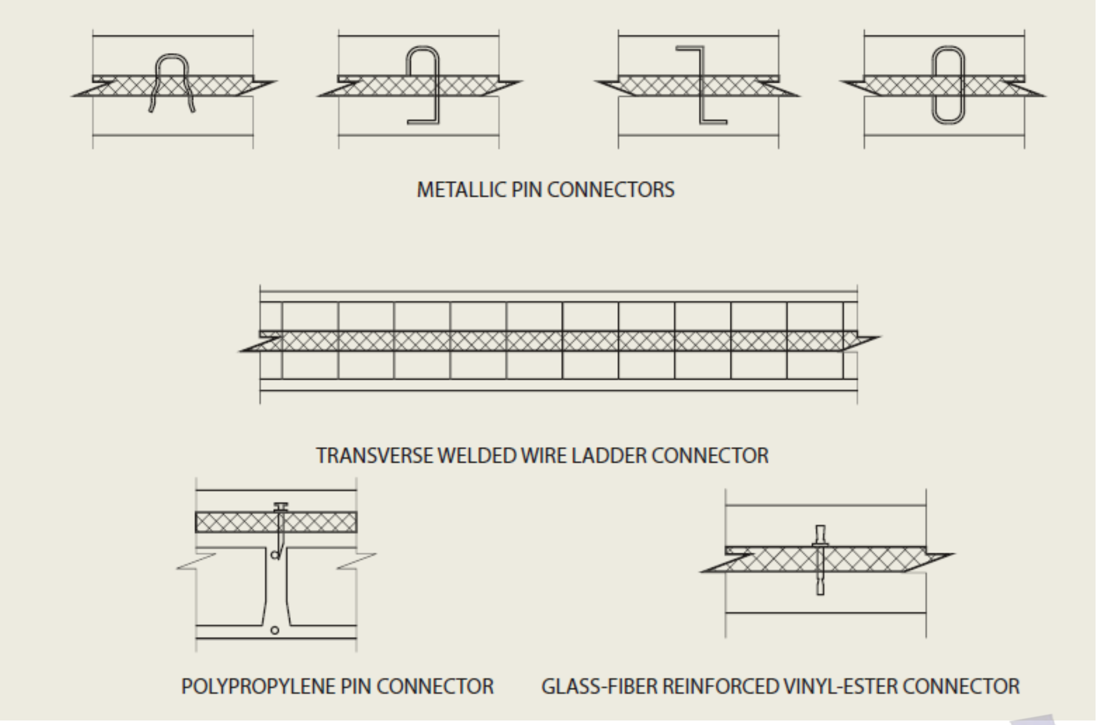


Figure 2.4: Non-composite connectors
(PCI Journal Spring 2011)

2.3 Precast Concrete Sandwich Panel

A sandwich panel is a three-layer element, comprising of two thin, flat facing plates of high-strength material and between which a thick lightweight core of low average strength is attached. Figure 2.5 presents a several types of sandwich panel elements (An Chen, 2004). Such sandwich structures have gained widespread acceptance within the aerospace, naval/marine, automotive and general transportation industries as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength and high buckling resistance (Mahfuz et al., 2004).

The concrete wvthes 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 2.6 shows a typical 3-D view of a sandwich panel with truss shaped shear connectors.

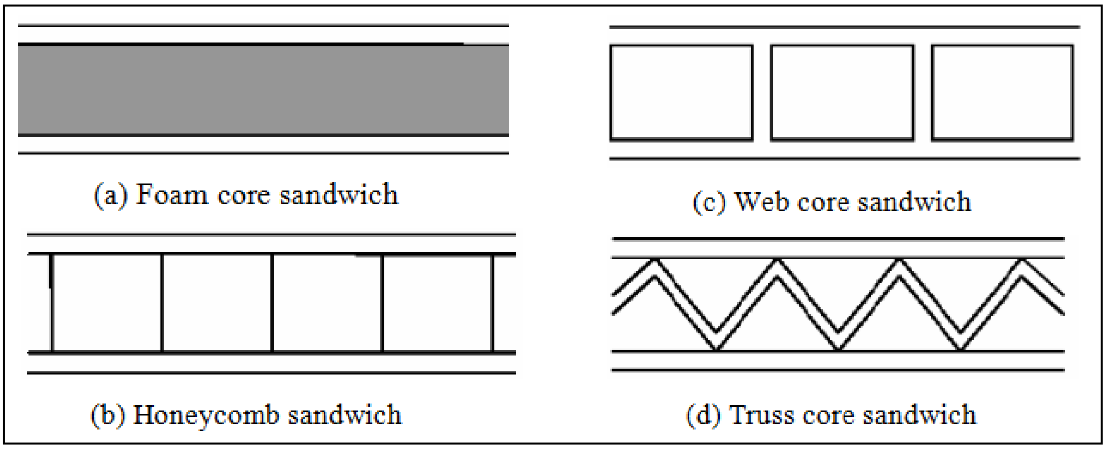


Figure 2.5**:** Types of sandwich elements

(An Chen, 2004)

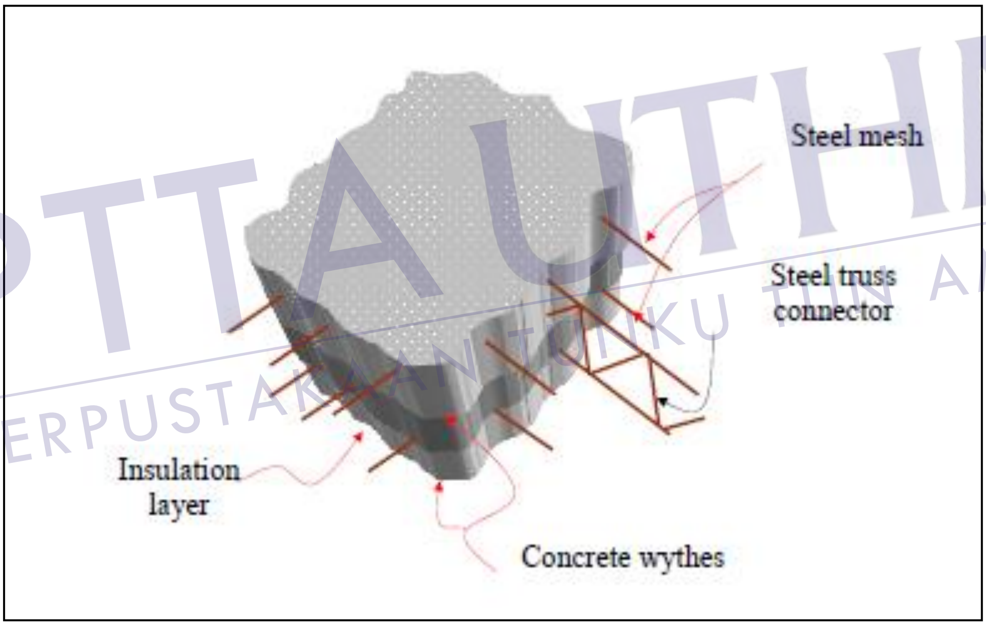


Figure 2.6: Precast concrete sandwich panel in 3-D

(Benayoune A et al., 2006)

2.3.1 Advantages Of Sandwich Panels

Sandwich construction form has distinct advantages over conventional structural sections because it promises high stiffness and high strength-to-weight ratio (Tat and Qian, 2000; Araffa and Balaguru, 2006) as compared with a solid member. Sandwich composite structure possesses excellent flexural and shear properties. Their inherent lightweight characteristics make them ideal structural components where weight reduction is desirable (Serrano et al., 2007). Thus structural sandwich panels are becoming important elements in modern lightweight construction.

In concrete construction, self-weight of structure represents a very large proportion of the total load on the structures (Mouli and Khelafi, 2006). Thus reduction in the self-weight of the structures by adopting an appropriate approach results in the reduction of element cross-section, size of foundation and supporting elements thereby reduced overall cost of the project. The lightweight structural elements can be applied for construction of the buildings on soils with lower load-bearing capacity (Carmichael, 1986).

Reduced self-weight of the structures using lightweight concrete reduces the risk of earthquake damages to the structures because the earth quake forces that will influence the civil engineering structures and buildings are proportional to the mass of the structures and building. Thus reducing the mass of the structure or building is of utmost importance to reduce their risk due to earthquake acceleration (Ergul et al., 2004). Among the other advantages, its good thermal insulation due to the cellular thick core makes it an ideal external construction component (Bottcher and Lange, 2006). Some recent investigations suggest their excellent energy-absorbing characteristics under high-velocity, impact loading conditions (Villanueva and Cantwell, 2004). Sandwich structures have been considered a potential candidate to mitigate impulsive (short duration) loads (Nemat-Nasser et al., 2007).

2.3.2 Description of Sandwich Panel Types

(i) Non-Composite: A non-composite sandwich panel is analyzed, designed, detailed, and manufactured so that the two concrete wythes act independently. Generally, there is a structural wythe and a nonstructural wythe, with the structural wythe being the thicker of the two.

(ii) Composite: Composite sandwich panels are analyzed, designed, detailed, and manufactured so that the two concrete wythes act together to resist applied loads. The entire panel acts as a single unit in bending. This is accomplished by providing full shear transfer between the wythes.

(iii) Partial Composite: Partial composite sandwich panels have shear ties connecting the wythes, but the connectors do not provide full composite action. The bending stiffness and strength of these panel types fall between the stiffness and strength of full composite and non-composite sandwich panels. Figure 2.7.

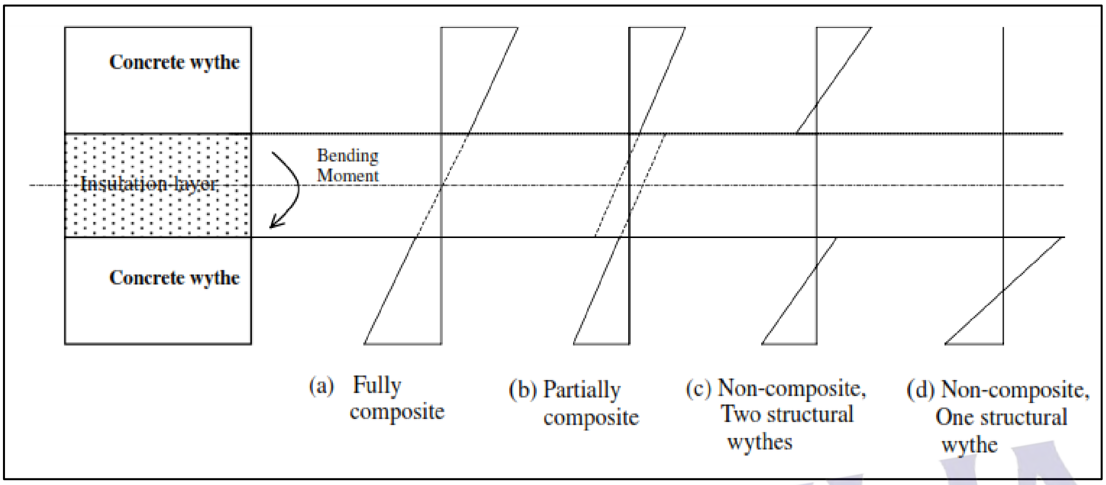


Figure 2.7: Strain distribution in sandwich panel under flexure (Benayoune, A et al, 2008)

2.4 Previous Studies

2.4.1 Sandwich Panels

According to Bush & Stine (1994), six precast concrete sandwich panels with continuous truss connectors were tested. The primary variables of the test included number, orientation, and spacing of the shear connectors. The test showed that a high degree of composite stiffness and flexural capacity could be achieved with truss connectors oriented longitudinally in the panel. The test also revealed that shear was transferred through stripping and handling inserts as well as through the solid concrete ribs. It was further shown that a friction bond between insulation and concrete provided a contribution to the overall shear transfer.

Einea *et al.* (1994) investigated experimentally and analytically with a newly developed PCSP system with high thermal resistance and optimum structure performance by provided a connector that was made of fiber reinforced plastic bent bar (FRPBB) and chords that were pre-stressed steel stands as shown in Figure 2.8.

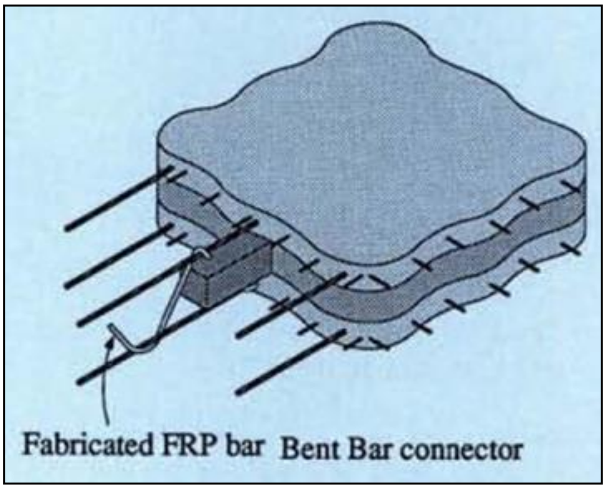


Figure 2.8: FRPBB connector

(Einea et al, 1994)

The experiment comprised of full scale panel testing by flexural loading and small scale specimens by pure shear and flexural loading, Table 2.1 shows the details of each panel.

Table 2.1: Details of panel testing by flexural load

(Einea et al, 1994)

Full scale	Parameters of panels						
Two Panels	h(m)	t (mm)	w (m)	EPS	FRPBB connector	LP_1	LP_2
	9.14	204	2.44	76	10 mm	3	8.9
Where h; high, t; thickness, w; wide, EPS; expended polystyrene insulation, LP_1; load of panel 1(kPa), LP_2; load of panel 2 (kPa),							

The full scale test was carried out to investigate the structure behaviour of the new development subjected to uniformly distributed load. Three of the five strands in each panel were used as chords for the FRPBB connector and the panel performed as full composition action. The observation was that the panel behaved linearly up to pressure load 2.9 kPa, Figure 2.9 showed that the high initial stiffness of the panel corresponded to the stiffness computed assuming the diagonals were rigidly embedded in the concrete wythes. The decrease in stiffness that occurs at 2.9 kPa corresponded to the computed panel stiffness and load above 3.8 to 4.8. Cracking of the wythes further reducde the stiffness of the panel.

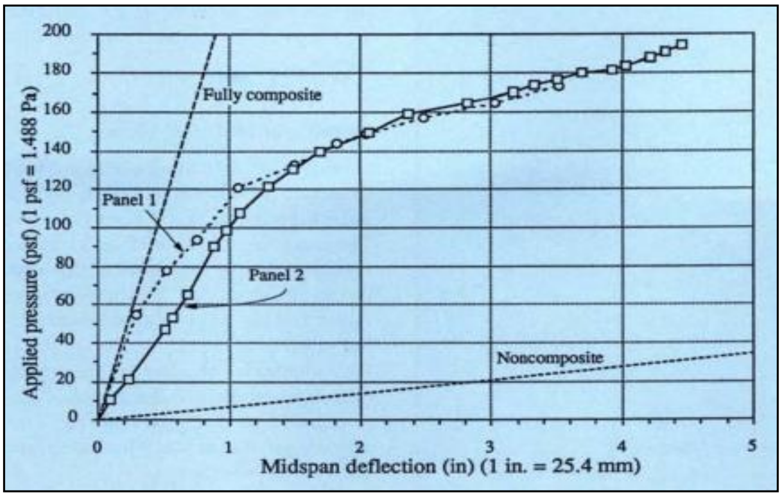


Figure 2.9: Applied load vs. mid-span displacement relationship

(Einea et al, 1994)

Small scale tests were conducted to assess the behaviour of the FRPBB connector. The study comprised of shear and flexure tests. Figure 2.10 shows the details of panels that were used for shear test and the test was carried out by using sequence of pure shear testing as shown in Figure 2.11. Table 2.2 shows the details of each panel.

Table 2.2: Details of panels
(Einea et al, 1994)

Small scale	Parameters of panels						
	EPS		*fc'* (MPa)	FRPBB connector	Load (KN)	Re-L (KN)	*EI*
Panel 1	Faced with bond breaker sheets	76mm	42.7	10 mm	24.9	28.2	594
Panel 2	Un-faced insulation				-	35.6	924
Where L; load, Re-L; reloaded to failure, *EI;* elastic stiffness (KN-m^2)							

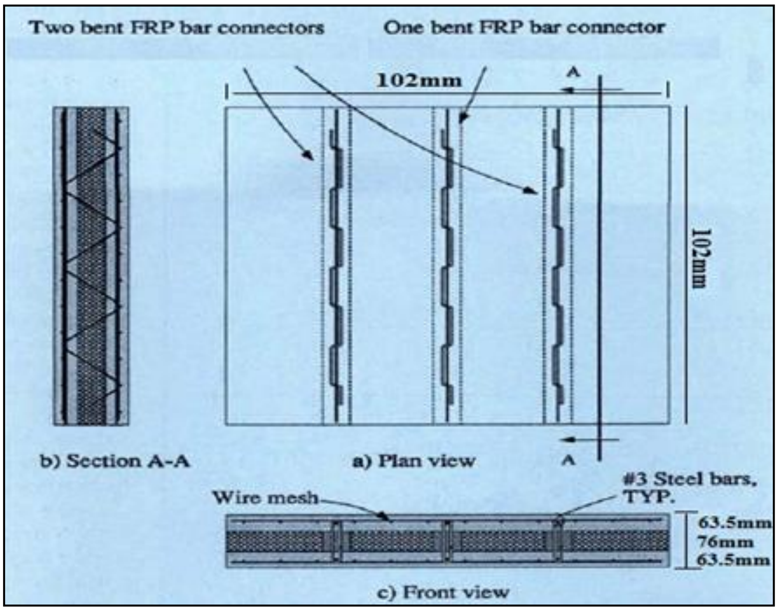


Figure 2.10: Details of shear specimens

(Einea et al, 1994)

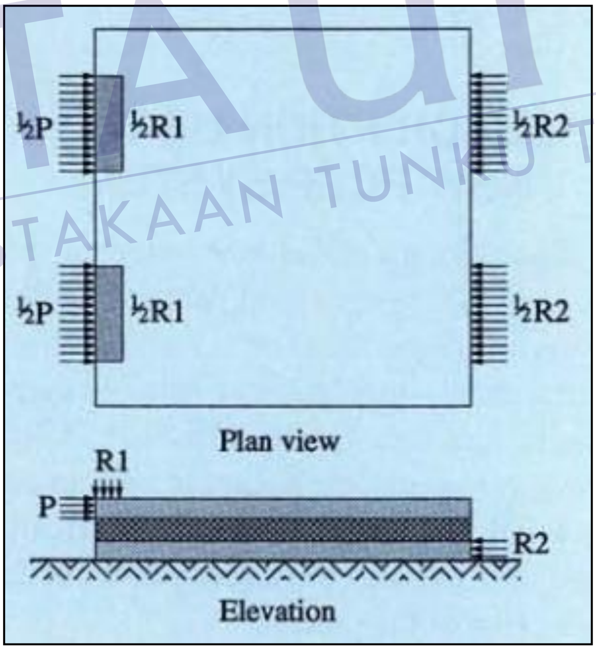
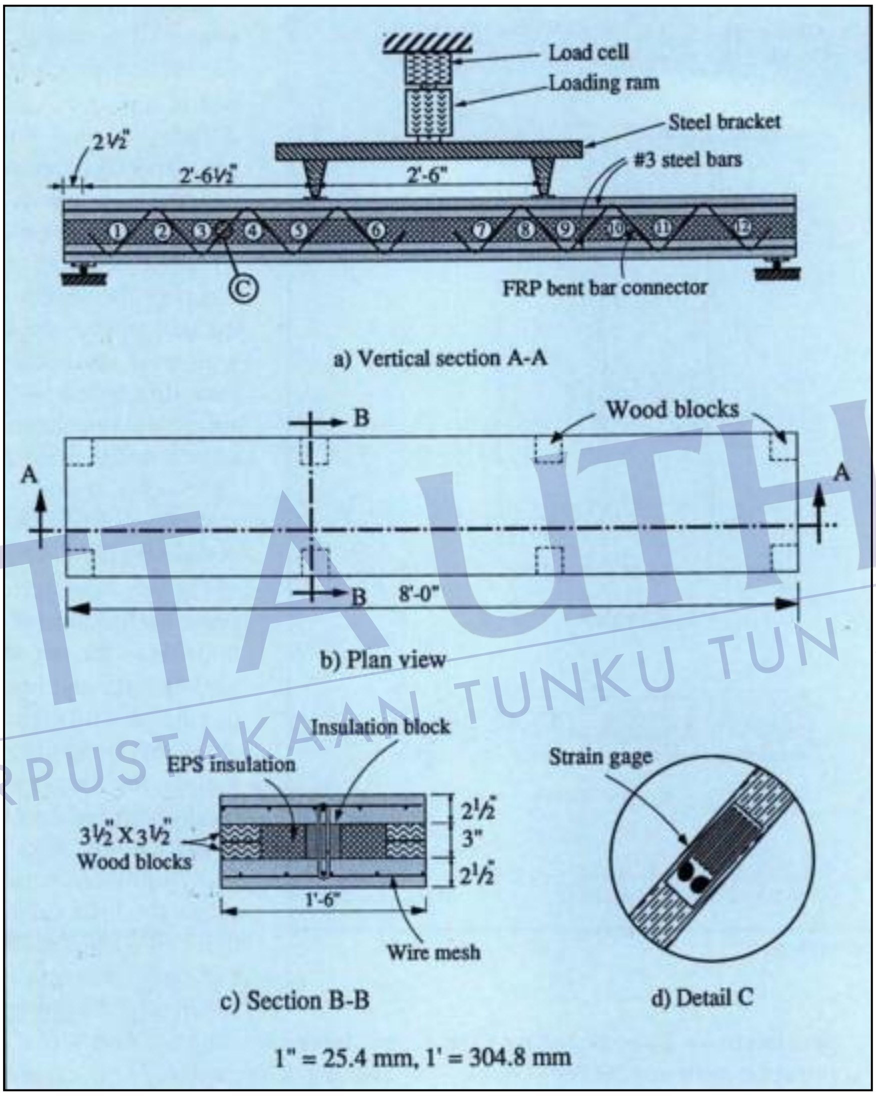


Figure 2.11: Panel under shear test

(Einea et al, 1994)

The significant observations of shear testing show that the axial strength of the connector governs the shear strength of specimens and no failure occurs in the wythes. The majority of the FRPBB connectors failed at the portions of the diagonals falling within the insulation layer due to flexural combined with axial compression. Small scale flexural tests were performed to explore the behaviour of the FRPBB connectors in flexure; Figure 2.12 shows the details of the panel under concentrated load, supported by a steel roller at each end.



a) Vertical section A-A

b) Plan view

c) Section B-B

d) Detail C

1" = 25.4 mm, 1' = 304.8 mm

Figure 2.12: Flexure test setup
(Einea et al, 1994)

As shown in Figure 2.13, the observation was that most of the cracks are concentrated at the located of the peak moment in each wythes, For panel 1; the first crack was at the bottom of surface of the bottom of wythe at a load 8.9 KN while the cracking in the top wythe occurred at load 17.3 KN. For panel 2; cracks initiated in the bottom wythe at a load of 15.6 KN and in the top wythe at a load of 23.6 KN; the shear strength contribution of the unfaced insulation increased the composite behaviour of the panel.

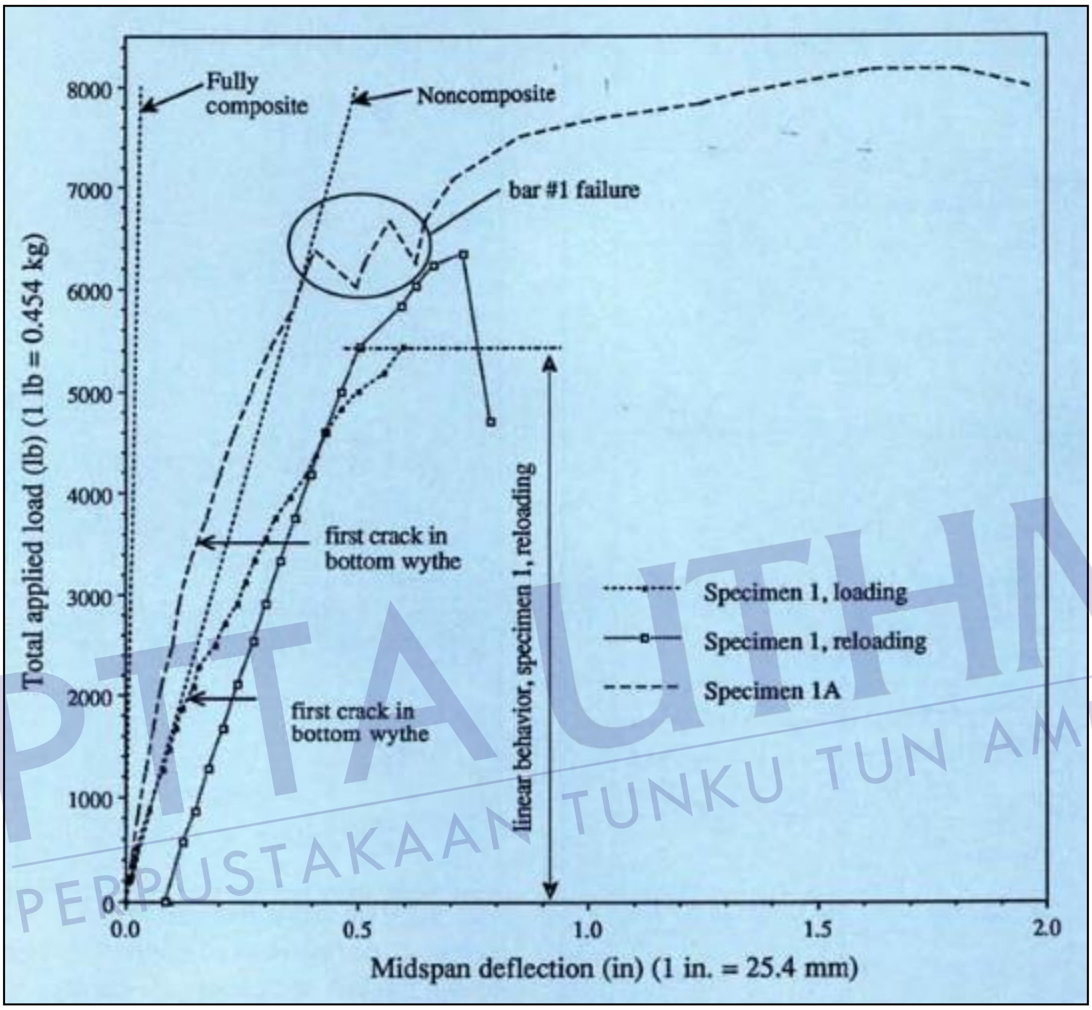


Figure 2.13: Load-deflection curves
(Einea et al, 1994)

The observation was also included the ultimate moment at the locations of the concentrated loads including self weight and steel bracket, are 12.1 and 15.0 KN-m for panel 1, 2 respectively. From the result that found that the load deflection relationship in the elastic range. The panels behaved as non-composite (65 percent composite of panel 1 and 81 for panel 2) system at the elastic stress level although their ultimate strength was close to the composite ultimate strength. The behaviour indicated that the FRP bars slip inside the concrete at early stages of load. The force increase gradually in these bars as the load increases until their strength is reached at the ultimate strength of the specimens. This behaviour can reduce the bowing due to the differential temperature conditions of sandwich panels during their service life. In a compression with the full scale flexural test, the full scale panels are much stiffer than in small scale.

An analytical investigation using FEM linear and nonlinear material models of the tested small scale specimens indicates that the load displacement curve obtained is very similar to the experiment obtained as shown in Figure 2.14.

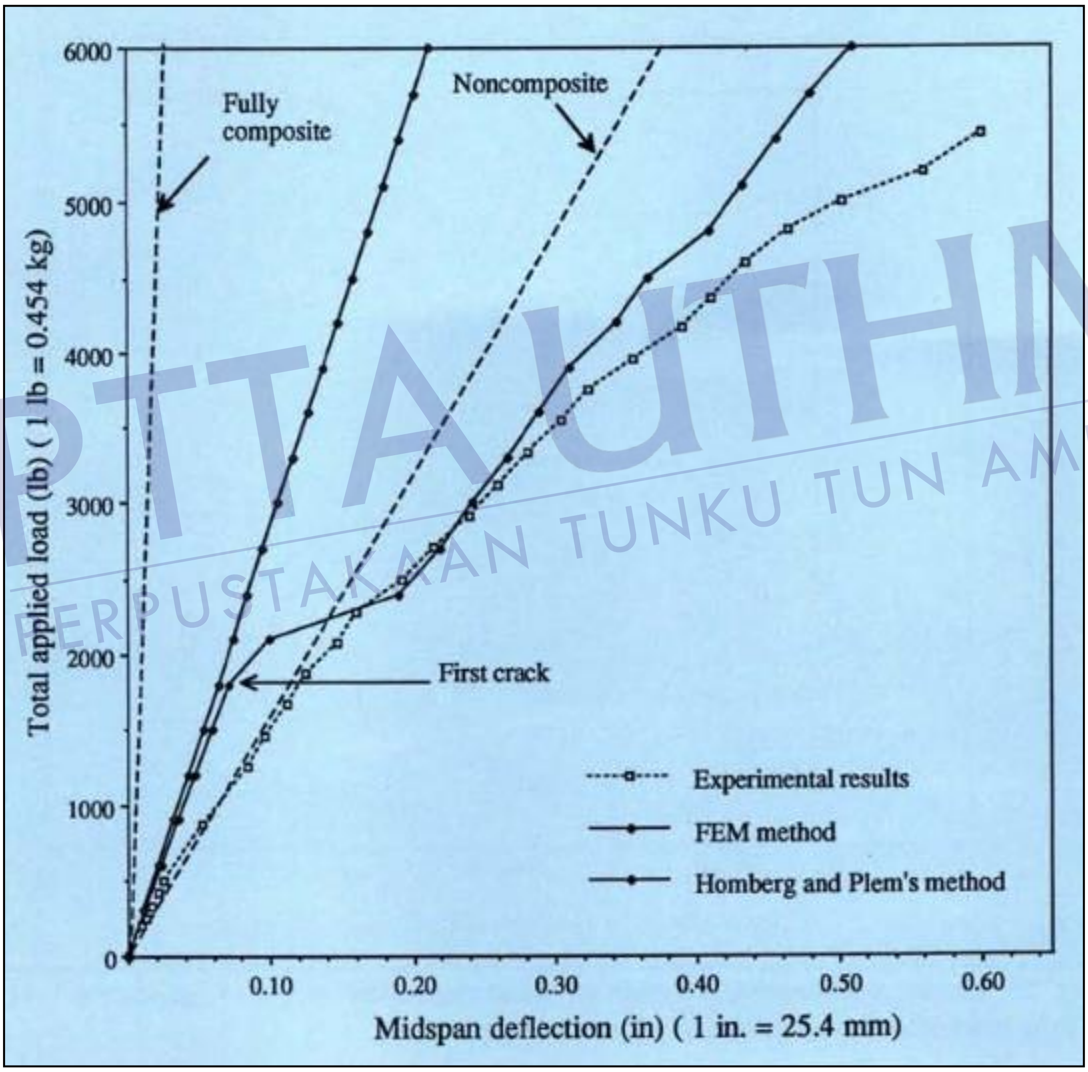


Figure 2.14: FEM’s load deflection curve

(Einea et al, 1994)

From the experimental and analytical investigations it was found that the result from FEM and from theory elasticity equations correlated well and showed that the developed panels system met the objective of the study.

Pokharel & Mahendran (2003) carried out an experimental investigation and design of sandwich panels subjected to local buckling and post buckling effects. The sandwich panel was made of polystyrene foam core and high strength steel faces. The steel plates were glued to the foam core by using a suitable adhesive. A series of compression test were conducted on flat steel plate elements with various b/t ratios from 50 to 500 as shown in Figure 2.15.

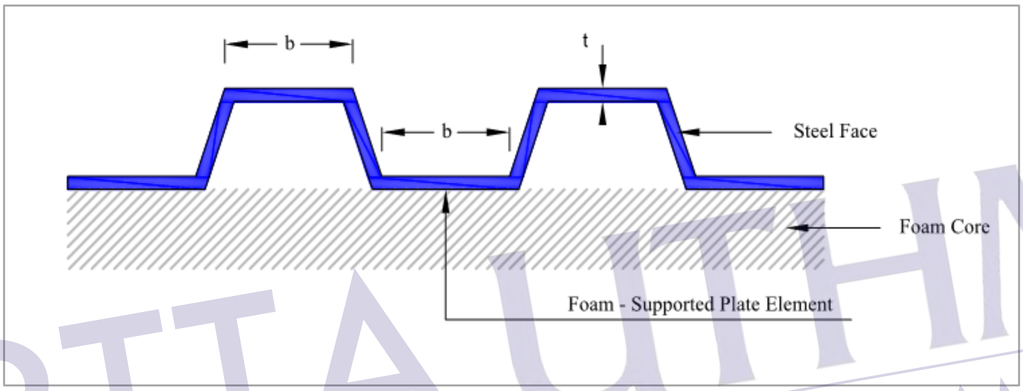


Figure 2.15: Critical b/t ratios of profiled sandwich panel for local buckling (Pokharel and Mahendran, 2003)

The experiment was conducted for two grades of steel; mild steel with yield strength of 250 MPa and high strength steel with yield strength of 550 MPa. Results revealed that the sandwich panel with low b/t ratio is adequate to resist local buckling. It was observed that all the specimens failed in a similar manner with the continuous application of the compression load.

According to Pessiki & Mlynarczyk (2003), four full scale of PCSP were tested. The first panel was a typical precast, prestressed concrete sandwich panel that had shear connector provided by regions of solid concrete in the insulation wythe, metal wythe connector(M-ties), and bond between the concrete wythes and the insulation wythe. It was found that the solid concrete region provide most of the strength and stiffness that contribute to composite behaviour. Steel M-ties connectors and bond between the insulation and concrete contribute relatively little to composite behaviour. Therefore, it is recommended that solid concrete region be proportioned to provide all of the required composite action in precast sandwich panel wall.

Kabir (2005) investigated the structural performance of shotcrete lightweight sandwich panels with compressive strength of 12 MPa and tensile strength of 1.2 MPa under shear and bearing loads. The sandwich panels consisted of shotcrete wythes which enclose the polystyrene core. Three specimens are provided for horizontal bending tests, each sandwich panel is 300 cm long and 100 cm wide with the upper and lower concrete wythes at 6 and 4 cm thick respectively. It was reinforced by the diagonal 3.5 mm cross steel wires welded to the 2.5 mm steel fabric embedded in each wythe as shown in Figure 2.16. Tests for flexural and direct shear loading were carried out based on ASTM E-72 and ASTM 564 respectively.

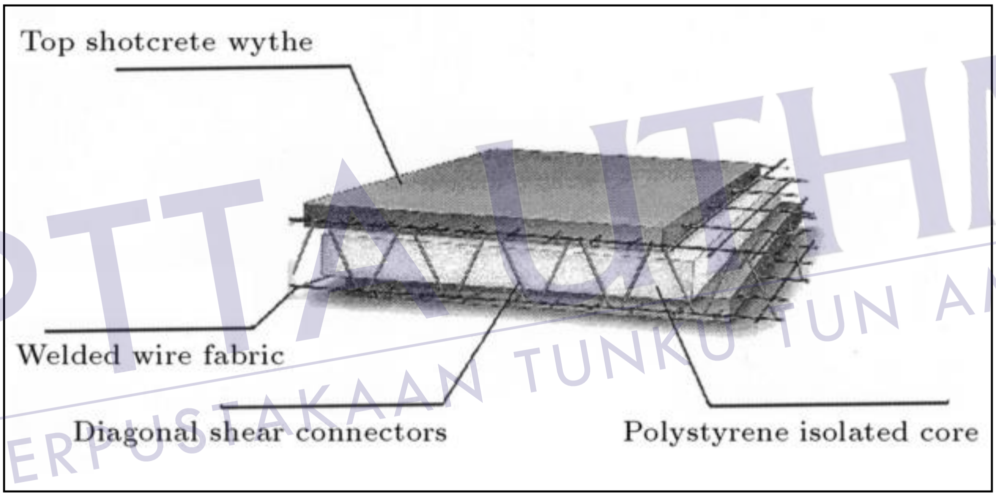


Figure 2.16: Shotcrete lightweight sandwich panel
(Kabir, 2005)

The loading points on the specimens are placed at L/4 and 3L/4, of the slab span as shown in Figure 2.17. From the experiment, it was found that the crack propagates to the upper layer, at 1200 kg load. The bottom mesh was yielded and the crushing of concrete caused the instability of the panel. The maximum load was recorded at 2200 kg. Table 2.3 shows the ultimate loads and their corresponding displacement of slabs for the horizontal flexural test.

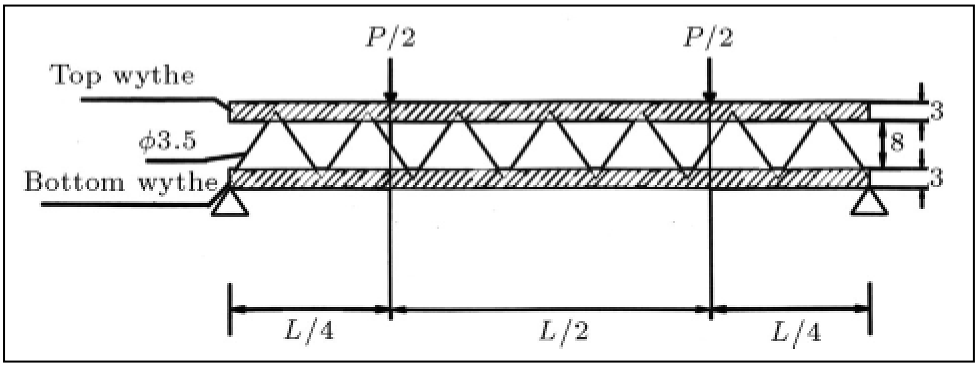


Figure 2.17: Geometry and applied boundary condition assumed for panel.
(Kabir, 2005)

Table 2.3: Experimental results for bending test
(Kabir, 2005)

Specimen No	Thickness (cm)	Type of Shotcrete	Cement Content	p_u (Kg)	Max. Deflection (mm)
Slab-1	16	Manual	300 kg/m³	2200	80
Slab-2	16	Manual	300 kg/m³	1900	40
Slab-3	16	Manual	300 kg/m³	1800	80

Benayoune A et al (2006) studied the behaviour of precast reinforced sandwich wall panels with slenderness ratio varying from 10 to 20 under the influence of eccentric load. Total of six panel specimens with various slenderness ratios, H/t, were cast and tested tinder eccentric load. The test results were analysed in the context of load bearing capacity, load-deformation profiles, load-strain curves, cracking patterns and the mode of failure. It was observed that all test panels ultimately failed by crushing. The first crack was noticed to occur at about 38 to 55 percent of the failure loads. It was also found that the failure modes of the six panels showed separation of the two concrete wythes near the upper part of the wall. Both concrete wythes of sandwich panels deflected together up to the point of failure. Higher lateral deflections were recorded in the specimen with higher slenderness ratio. It was observed that the ultimate strength of the panel decrease nonlinearly with the increase in the slenderness ratio as shown in Figure 2.18.

REFERENCE

American Concrete Institute. *building code requirements for structural concrete and commentary*. USA, ACI 318-05, section 17.5.3. 2005.

An Chen. *Strength Evaluation of Honeycomb FRP Sandwich Panels with Sinusoidal Core*. Ph.D. Thesis. Department of Civil and Environmental Engineering West Virginia University; 2004.

Belén González &Fernando Martínez. Shear Strength Of Concrete With Recycled Aggregates. (2001). School of Civil Engineering, University of A Coruña (ETSICCP, UDC), Spain.

Benayoune A, A. Aziz A. Samad, D.N. Trikha, A. Abdullah Abang Ali, and A.A. Ashrabov. Structural behaviour of eccentrically loaded precast sandwich panels. *London: Elsevier*. 2006. 20(9): 713-724.

Benayoune A, A.A.A. Samad, A.A. Abang Ali and D.N. Trikha d. Response of Pre-cast Reinforced Composite Sandwich Panels to Axial Loading. *London: Elsevier*. 2007. 21(3): 677-685.

Benayoune A, A. Aziz A. Samad, D.N. Trikha, A.A. Abang Ali, and A.A, and S.H.M. Ellinna. Flexural Behaviour of Pre-cast Concrete Sandwich Composite Panel- Experimental and Theoritical Investigations. *London: Elsevier*. 2008. 22(4): 580-592.

Bottcher, M. and Lange, J. Sandwich Panels with Openings. *Composite Construction in Steel and Concrete*. 2006. 186(14): 137-46.

Bush T.D. and Stine G.L. Flexural Behaviour of Composite Precast Concrete Sandwich Panels with Continuous Truss Connector. *PCI Journal*. 1994. 39(2): 112-121.

Carmichael, J. Pumice Concrete Panels. *Concrete International*. 1986. 8(11): 31-32.

Einea A, Salmon. David C., Tadros Maher K. and Culp T. A new structurally and thermally efficient precast sandwich panel system. *PCI Journal*. 1994. 38(4): 90-101.

Ergul, Y., Cengiz, D.A., Aleaettin, K. and Hassan, G. Strength and Properties of Lightweight Concrete Made with Basaltic Pumice and Fly Ash. *Materials Letters*. 2003. 57(15): 2267-2270.

Farmington Hills, Michigan (2001). *Recycled concrete aggregate*. ACI Committee 555 Report, American Concrete Institute

Fisher, C.; Werge, M. *EU as a Recycling Society*; ETC/SCP Working Paper 2/2009; Available online: http://scp.eionet.europa.eu.int (accessed on 14 August 2009).

Ismail Abdul Rahman. Assessment of Recycled Aggregate Concrete. *Modern Applied Science*. 2009. 3(10).

J. M. Davies, *Lightweight Sandwich Construction*, Oxford:Blackwell Science Ltd. (1997).

Karim S. Numayra, Yousef S. Al Rjoub, Abdalla M. Qudah, and Khair Al-Deen I. Bsisu. Resistance of exterior three-dimensional walls to high velocity projectiles. *London: Elsevier*. 2012. 48 (8): 3431–3435.

Kheder, G.F. and Al-Windawi, S.A. *Variation in Mechanical Properties of Natural and Recycled Aggregate Concrete as Related to the Strength of Their Binding Mortar* Materials and Structures 38 (August-September 2005), pp. 701-709.

M.Z. Kabir. Structural Performance of 3-D Sandwich Panels Under Shear and Flexural Loading. *Sharif University of Technology: Journal of Scientia Iranica*. 2005. 12(4): 402-408.

Mahfuz, H., Muhammad, S.I., Vijaya,,K.R, Mrinal, C.S. and Shaik J. Response of Sandwich Composites with Nanophased Cores under Flexural Loading. *Composites: Part B Engineering*. 2004. 35(6-8): 543-550.

Mirjana Malešev, Vlastimir Radonjanin and Snežana Marinković. Recycled Concrete as Aggregate for Structural Concrete Production. *Sustainability*. 2010. (2): 1204-1225.

Mohammed A. Mousa and Nasim Uddin. Experimental and analytical study of carbon fiber-reinforced polymer (FRP)/autoclaved aerated concrete (AAC) sandwich panels. *London: Elsevier*. 2009. 31(10): 2337-2344.

Mouli, M. and Khelafi, H. (2006). Strength of Short Composite Rectangular Hollow Section Columns Filled with Lightweight Aggregate Concrete. *Engineering Structures*. Article in Press, Available Online on www.sciencedirect.com**.**

Nemat-Nasser, S., Kang, W.J, Mc Gee, J.D., Guo, E.G. and Isaacs. Experimental Investigation of Energy-Absorption Characteristics of Components of Sandwich Structures. *International Journal of Impact Engineering*. 2007. 34(6): 1119-1146.

Noridah Mohamad, Wahid Omar and Redzuan Abdullah. Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) Tested Under Axial Load. *Journal of Advanced Materials Research*. 2011. 1153-1162.

PCI Committee. State of the Art of Precast/Prestresses Sandwich Wall Panels. *PCI Journal*. 1997. 42(2): 92-133.

PCI Committee. State of the Art of Precast/Prestresses Sandwich Wall Panels. *PCI Journal*. 2011. 141-145.

Pessiki S. and Mlynarczyk A. Experimental Evaluation of The Composite Behaviour of Precast Concrete Sandwich Wall Panels. *PCI Journal*. 2003. 54-71.

Pokharel N. and Mahendran M. Experimental Investigation and Design of Sandwich Panels Subject To Local Buckling Effects. *Journal of constructional Steel Research. Elsevier*. 2003. 59 (12): 1533-1552.

S. Frondistou-Yannas. Waste Concrete as aggregate for New Concrete, *ACI Journal*. 1977. 14(8): 373–376.

Serrano, P., Juan, C., Uday K., Vaidya, A., and Nasim U. Low Velocity Impact Response of Autoclaved Aerated Concrete/CFRP Sandwich Plates. *Composite Structures*. 2007. 80(4): 621-630.

Suraya, H. A., Lee, Y.L., Ismail, A. R., Hamidah, M. S. and Mia, V.S. *Compressive strength of recycled Aggregate to concrete with various Percentage of recycled aggregate*. Universiti Tun Hussein Onn Malaysia; 2007.

Tat, L.S and Qian, H C. Elastic Stiffness Properties and Behaviour of Truss Core Sandwich Panel. *ASCE Journal of Structural Engineering*. 2000. 126(5): 552-559.

Transportation Applications of Recycled Concrete Aggregate—FHWA State of the Practice National Review 2004; U.S. *Department of Transportation Federal Highway Administration*: Washington, DC, USA, 2004; pp. 1-47.

Villanueva, GR and Cantwell, W.J. The High Velocity Impact Response of Composite and FML-Reinforced Sandwich Structures. *Composite Science and Technology*. 2004. 64(1): 35-54.