UNIVERSITI PUTRA MALAYSIA

DETERMINATION OF STRUCTURAL BEHAVIOR OF PRECAST FOAMED CONCRETE SANDWICH PANEL

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Chairman : Assoc. Prof. Ir. Raizal Saifulnaz Muhammad Rashid, PhD
Faculty : Engineering

Precast Foamed Concrete Sandwich Panel (PFCSP) has the ability to act as a wall bearing and flooring element that complies with the requirements of structural efficiency and thermal insulation of building components. It has the potential for use as an industrialised building system component for low-rise residential buildings.

The development of housing remains a major worldwide challenge for construction industries in many countries due to financial constraints and lack of appropriate technologies. The problem is further compounded by rapid increase of population. Also, the existing precast concrete sandwich panels act in a semi-composite behavior due to several factors related to shear connectors used. Therefore, a study to improve on the structural composite performance is extremely required, as most of the current precast concrete structures are deemed as heavy systems. Hence, the reduction on the self-weight of PCSP becomes highly imperative, particularly for use at construction sites with low load-bearing capacity grounds.

This study has the objectives to determine the parameters related to structural behavior of PFCSP served as load-bearing wall and floor systems. The study also determines the properties of foamed concrete for use in the production of PFCSP. In order to evaluate the performance of the developed PFCSP elements, PFCSPs were subjected to loads in various directions, including axial, in-plane and out-of-plane loads. An analytical study and experimental tests were conducted to evaluate the structural performance of the PFCSPs subjected to loads in various directions. An experimental study comprising thirty (30) PFCSPs and three (3) PCSPs with one panel was set as control, as each test was conducted under three different full-scale loadings (12 PFCSPs under axial load, 6 PFCSPs under in-plane shear load, and 12 PFCSPs under out-of-plane load). Foamed concrete with 24.83 MPa and 25.73 MPa was obtained as the potentially viable grades to produce the structural concrete wythes of the PFCSPs as load-bearing wall and slab elements, respectively. Foamed concrete wythes act as structural rigid elements. Important parameters, such as slenderness (H/t) and aspect ratios (L/d) were investigated using different variables.

The composite action under different imposed load conditions was studied and revealed a high structural composite performance. Further, a FEA parametric study was carried out to study similar parameters conducted via experimental tests to study the performance. Also, the theoretical investigations are conducted using design codes and theoretical expressions of previous researchers. Comparisons are made between the results obtained from experimental tests and non-linear FEA models studies for the purpose of validation.

Analysis of results found that the ultimate bearing strength was decreased by approximately 26.3% and 111% for an increase of H/t from 14 to 24 and 13.33 to 28.57, respectively, as obtained from experimental works. However, using the 2-D FEA simulation models, the bearing capacity was decreased by almost 9.9% and 89%. Under in-plane shear load, the reduction in ultimate in-plane strength was approximately 36.14% and 28.07% for an increase of H/t from 14 to 24, as obtained from tests and the 2-D FEA models, respectively. The ultimate bearing capacity of the developed PFCSP walls was obtained to be at least 9 times larger than the required, to resist typical two-storey ultimate design loads. Furthermore, it has been found that the ultimate flexural strength capacity was decreased by around 50% and 52.3% with an L/d increase from 18.33 to 26.67 and from 16.18 to 23.53 of the two identical PFCSP groups with the depths of 150 and 170 mm, respectively, as obtained experimentally. Verification of the result using the 2-D FEA simulation models indicated a reduction in ultimate strength capacity of about 69.6% and 79.2%, respectively.

Therefore, it is concluded that the developed PFCSP is suitable as a load bearing element, and can be applicable and safe for a wall system for two-storey buildings, and PFCSP has a practical use as floor slabs. The summary and conclusions of the major findings of this study together with the recommendations for further work are presented in Chapter VII.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MENENTUKAN KELAKUAN STRUKTUR PANEL SANDWIC KONKRIT BERBUSA PRATUANG

Oleh

MUGAHED YAHYA HUSSEIN AMRAN

November 2016

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Panel Sandwic Konkrit Berbusa Pratuang (PFCSP) mempunyai kemampuan utk bertindak sebagai dinding penahan dan elemen lantai yang memenuhi keperluan kecekapan struktur dan penebat haba untuk komponen bangunan. Panel ini mempunyai potensi untuk digunakan sebagai komponen sistem pembinaan industri untuk bangunan bertingkat.

Pembangunan rumah kediaman sememangnya menjadi satu cabaran utama bagi industri pembinaan di kebanyakan negara disebabkan oleh kekangan kewangan dan teknologi yang sesuai. Masalah ini semakin meruncing dengan pertambahan penduduk. Panel sandwic konkrit bertetulang pratuang yang sedia ada mempuyai sifat komposit separa disebabkan beberapa faktor yang berkait dengan penyambung ricih. Oleh itu, suatu kajian untuk menambahbaik prestasi struktur komposit sangat diperlukan kerana konkrit pratuang konvensional menghasilkan struktur yang sangat berat. Dengan itu, (PFCSP) berpotensi untuk mengurangkan berat-siri struktur, yang sangat penting bagi kawasan tapak pembinaan yang mempunyai keupayaan galas yang rendah.

Kajian ini mempuyai objektif untuk menentukan parameter yang berkaitan dengan kelakuan struktur PFCSP untuk digunakan sebagai sistem dinding penahan dan lantai. Kajian ini juga menentukan sifat konkrit berbusa bagi kegunaan penghasilan PFCSP. Untuk menilai prestasi aplikasi komposit yang telah dihasilkan ini, panel PFCSP telah dikenakan beban dalam pelbagai arah, termasuklah beban paksian, dalam-satah and luar-satah. Kajian berbentuk analitik dan ujikaji telah dilaksanakan untuk menilai prestasi PFCSP yang dikenai beban pelbagai arah. Ujikaji yang melibatkan tiga puluh (30) panel PFCSP dan tiga (3) panel PCSP, dengan sekeping sebagai panel kawalan, dilakukan di bawah tiga bebanan skala-penuh yang berbeza (12 panel PFCSP dikenai beban paksian, 6 panel PFCSP dikenai beban ricih dalam-satah dan 12 panel PFCSP dikenai beban luar-satah). Konkrit berbusa dengan gred kekuatan 24.83 MPa and 25.73 MPa telah dihasilkan untuk menyamai struktur wythe

konkrit PFCSP yang masing-masing sesuai sebagai elemen tembok penahan dan papak.

Wythes konkrit berbusa bertindak sebagai element struktur tegar. Parameter utama seperti nisbah kelangsingan (H/t) dan nisbah bentuk (L/d) telah diteliti menerusi beberapa pembolehubah. Tindakan komposit di bawah pelbagai keadaan beban kenaan yang diselidik telah menemukan struktur komposit berprestasi tinggi. Selanjutnya, kajian parametrik menerusi Analisis Unsur Terhingga (FEA) telah dilakukan untuk mengesahkan prestasi tersebut menerusi ujikaji. Kajian secara teori dilaksanakan menerusi kod reka bentuk dan ungkapan teori daripada penyelidik terdahulu. Suatu perbandingan dilakukan antara keputusan ujikaji dengan model tak-linear FEA untuk tujuan validasi.

Analysis keputusan menunjukkan kekuatan galas muktamad dikurangi sebanyak lebih kurang 26.3% dan 111% dengan peningkatan nisbah H/t masing-masing dari 14 ke 24 dan dari 13.33 ke 28.57 daripada hasil ujikaji. Walau bagaimana pun dengan menggunakan model simulasi 2-D FEA, kekuatan galas telah berkurangan hampir 9.9% dan 89%. Di bawah bebanan ricih dalam-satah, pengurangan kekuatan dalam-satah muktamad ialah 36.14 dan 28.07% untuk peningkatan nisbah H/t dari 14 ke 24, seperti yang dihasilkan masing-masing daripada ujikaji dan model 2-D FEA. Keupayaan galas bagi dinding PFCSP yang dibangunkan ini didapati melebihi 9 kali kekuatan yang diperlukan, untuk merintangi beban reka bentuk bagi bangunan dua-tingkat. Keupayaan kekuatan lenturan muktamad juda didapati berkurangan sebanyak masing-masing 50% dan 52.3% dengan peningkatan nisbah L/d dari 18.33 ke 26.67 dan dari 16.18 ke 23.53 daripada dua kumpulan PFCSP yang serupa, dengan kedalaman masing-masing 150 mm and 170 mm, menerusi ujikaji. Keputusan telah diverifikasi menggunakan model simulasi 2-D FEA yang menunjukkan pengurangan keupayaan kekuatan muktamad masing-masing sebanyak lebih kurang 69.6% and 79.2%.

Oleh itu, lanya dapat disimpulkan bahawa PFCSP yang telah dibangunkan ini sesuai sebagai elemen penahan daya, dan selamat digunakan untuk sistem dinding bagi bangunan dua-tingkat, dan PFCSP mempunyai kegunaan praktikal sebagai elemen lantai. Ringkasan dan kesimpulan hasil dapatan utama dalam kajian ini, berserta saranan untuk kerja lanjutan kajian ini ada dinyatakan dalam Bab VII.

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MUGAHED AMRAN

I certify that a Thesis Examination Committee has met on 15 August 2016 to conduct the final examination of Mugahed Yahya Hussein Amran on his thesis entitled "Determination of Structural Behavior of Precast Foamed Concrete Sandwich Panel" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

IBS	Industrialised Building System
CIDB	Construction Industry Development Board
SIP	Structural Insulated Panel
PCSP	Precast Concrete Sandwich Panel
PCSWP	Precast Concrete Sandwich Wall Panel
PCSSP	Precast Concrete Sandwich Slab Panel
FC	Foamed Concrete
RC	Reinforced Concrete
PFCSP	Precast Foamed Concrete Sandwich Panel
FEM	Finite Element Method
FEA	Finite Element Analyses
ACI	American Concrete Institute
BS	British Standard
PCI	Precast/Prestressed Concrete Institute
HPC	High Performance Concrete
PAC	Pumice Aggregate Concrete
FRP	Fiber Reinforced Polymer
BRC	Steel Reinforced Fabric
EPS	Expanded polystyrene
ESG	Electrical Strain Gauges
LVDT	Linear voltage displacement transformers
2DIB	2D Straight Isoparametric Bar Element
2DIP	2D Isoparametric Plane Stress Element

LIST OF NOMENCLATURES

Δ	shear displacement or deflection due to out-of-plane load, mm
A	total area of the section, mm^2
a/c	ash/cement ratio
A_{cv}	gross area of concrete limited to thickness and length of the section, $b \times t$
A_g	gross area of the wall panel section, mm^2
A_h	Area of horizontal shear reinforcement, mm^2
A_s	area of tension reinforcement, mm^2
A_{sc}	area of compression steel, mm^2
A_{st}	area of tension steel reinforcement (for one-way), mm^2
A_{sv}	total cross sectional area of all bars throughout full width of panel, mm^2
A_w	upper wythe cross-sectional area, mm^2
b	width of the wall, mm
c	concrete cover, mm
$c_{content}$	cement content, kg/m^3
c_{in}	thickness of the insulation layer
d	depth of the section, mm
D	target plastic density, kg/m^3
d_1	depth of the section A_{s1} (for non-composite), mm
d_2	depth of the bottom wythe, mm
DD	dry density
E	modulus of elasticity, MPa
f	fine sand content, kg/m^3
F	total resisted force by tension and compression bars, N
FA/C	fly ash/cement
F_c	compressive force by concrete (composite), kN
F_{c1}	compressive force in concrete (non-composite), kN
f_{cu}	compressive strength of concrete, MPa
Fi/C	filler/cement
F_s	tension force by reinforcement (composite), kN
F_{s1}	force in tension reinforcement (non-composite), kN
f_y	yield strength of steel reinforcement, MPa.
g/l	gram/litre
H	height of the wall, mm
h	the height, mm
H/t	slenderness ratio
H_{eff}	effective height of the wall, mm
I	second moment of area of the equivalent concrete section, mm^4
I_g	cross moment of inertia, mm^4
K	0.8 reduction factor for wall restrained against rotation or the effective
shear	rigidity of connecting system for panel a unit area
$K/m.W$	Kelven per meter times Watt
K_{eff}	the effective shear rigidity of connecting system for panel a unit area
l	the length of the shear conector leg, mm
L/d	aspect ratio
M	applied bending moment; kN.m
M_u	ultimate moment capacity under flexural load, kN.m

n	the number of shear connectors or steel reinforcement bars used
P	the total horizontal applied forces resisted by all shear connectors used, kN
PC	Portland cement, kg/m^3
PD	plastic density
p_m	target casting density, kg/m^3
PP	polypropylene fiber
Q	moment area of wythe about centroid of panel, kN
q_u	interface horizontal force, kN
q_w	horizontal shear force per unit length, kN
RD_a	relative ash density, kg/m^3
RD_c	relative cement density, kg/m^3
RD_f	relative foam density, kg/m^3
RD_s	relative sand density, kg/m^3
s	0.9x, depth of neutral axis measured from the highly compressed face, mm
s/c	sand/cement ratio
s_1	0.9x, depth of neutral axis, for one wythe (non-composite), mm
s_2	spacing between steel bars, mm
s_{space}	spacing of shear connectors, mm
t	thickness of the wall, mm
TD	target density
T_u	axial foces acting on the leg of shear connctors, kN
V_c	shear strength provided by concrete, kN
V_f	volume of foam
V_n	total nominal shear strength capacity of the wall, kN
V_s	shear strength provided by steel, kN
V_u	factored shear force at the wall, kN
w	total mix water, kg/m^3
w/a	water/ash ratio
w/c	water/cement ratio
w/s	water/sand ratio
x	cement content, kg/m^3
α_c	is equal to $H/b \geq 2 = 0.17$ or when $H/b \leq 1.5 = 0.25$
γ	incline angel of shear connector
λ	0.85 for sand-lightweight concrete or 0.75 for all lightweight concrete
ρ_n	ratio of area of the distributed reinforcement parallel to the plane of A_{cv}
σ_{bottom}	the stresses at the bottom of the panel, MPa
σ_{top}	the stresses at the top face of the panel, MPa
ϕ	0.7 reduction factor for compression members
$\bar{Y}$	distance between the composite action and the upper wythe centroid, mm

CHAPTER I

INTRODUCTION

1.1 Industrialised building system

The global construction industry has undergone obvious transitional change from being an industry that employs conventional technology to one that uses a highly systematic and efficient system. The new system is known as the Industrialised Building System (IBS) (Nawi et al. 2014). The IBS is widely used in the Malaysian construction industry to obtain factory-produced structural elements, such as precast frames, roofs, and walls. The industry itself is well developed with some enterprises owning facilities for producing any precast structural element. In the Malaysian context, the Construction Industry Development Board (CIDB) defines the IBS as a system that comprises components that are generally prefabricated in-site or off-site at a factory by pouring concrete in a prepared formwork and leaving the concrete to cure in ambient conditions. The prefab components are then transported to the site for installation in designated positions in a structure with minimum additional manpower and site work. Nevertheless, the combination of precast IBS components still requires a minimum in situ to integrate their interactions with other elements, such as connection joints (Garrido et al. 2016). Recently, the production of precast concrete wall panels has become a specialization in the development of concrete products. For example, manufacturers remain on the lookout for new viable product lines. Architects and engineers appreciate the energy performance and general aesthetics of such panels. Contractors have also found that the use of sandwich panels allows quick drying, which in turn allows other trades to work in a clean and comfortable environment. The total population in Malaysia has rapidly increased. Meanwhile, the demand for improved quality of life has risen. For instance, the demand for residential buildings alone, as cited in the 1995–2020 Malaysia Plan, is estimated to be approximately 8,850,554 units, including 4,964,560 new housing units. This projection is based on the population increase (Yoke *et al*. 2003, Nawi *et al*. 2014). According to the 9th Malaysia Plan, 709,400 new residential units were projected to be built by 2009; of this number, 270,000 units (38.2%) were intended for low- and low/medium-cost houses, whereas the remaining 438,000 units (61.8%) were intended for medium and high residential building types (Nawi *et al*. 2011). However, Malaysia has been struggling to find a fast-track solution for building affordable quality housing units within the framework of sustainable development strategies and using technological means. As a result, the CIDB of Malaysia continues to encourage the construction industry to produce IBS components and thereby bridge the gap between population demands and industry supply. The IBS comprises two main components, namely, load bearing panels and flooring system elements (Figure 1.1). The two components are designed according to the principle of carrying the major loads transmitted from various parts of a completed building structure. Therefore, precast concrete panels fabricated for wall systems may be non- or load-bearing panels. Current applications are focused on ensuring the durability of external walls, quality performance, and low maintenance requirements.

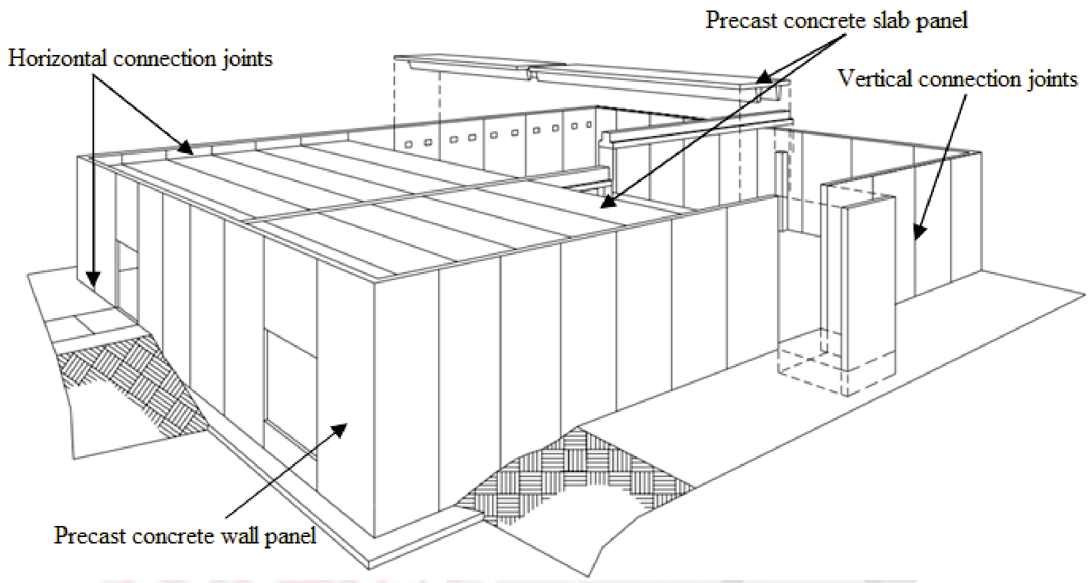

Figure 1.1: Industrial building system (IBS) (PCI Industry Handbook 6th Edition)

1.2 Precast concrete sandwich panel

The Precast Concrete Sandwich Panel (PCSP) is structurally and thermally efficient elements used for both walls and floor slab in multi-unit residential, commercial, and warehouse buildings throughout the world (Section 2.4). A typical PCSP consists of two precast reinforced concrete layers (called wythes) separated by a layer of insulation and connected with connectors which penetrate the insulation layer. PCSP is majority advanced for use as a wall bearing because of its capacity to withstand loads that act from the roof or floor of the building elements and to transfer these loads directly to the foundation (Noridah, 2010). The valuable functions of PCSPs are highly similar to those of precast solid wall panels, and they differ only in their build-ups. An interest in sandwich panels as bearing wall has been recently observed, leading manufacturers to search for sufficient viable products. Engineers/architects and researchers are pleased with the structural efficacy, insulation efficiency, and energy performance of wall/slab sandwich panels (Voellinger *et al.* 2014). Further, PCSP is a fast-track construction technique that was introduced to a number of western countries, including the United Kingdom, the United States, Germany, and Holland, in the past century (Salmon, 1997, PCI, 2011). PCSPs are considered a viable technology product for replacing the conventional applications of pure cast *in-situ* structural concrete with prefabricated building applications. A PCSP typically comprises two high-strength wythes that are separated by a layer with less weight, low strength, and low density (PCI, 2011). These wythes come in standard shapes and sizes and may thus include a hollow core section, a double tee and a flat slab or any other architectural section connected by a series of shear connectors, metal connectors, and concrete ribs. According to the PCI Committee (2011), PCSPs are practically prefabricated with heights and widths of up to 13.5 m and 3.5 m, respectively. The thickness of each concrete wythe ranges from 0.05 m to 0.152 m, and the overall thickness of the panel ranges from 0.127 m to 0.305 m. According to EN BS5427:1976, the minimum thickness of a structural wythe is 76 mm for a non-pre-stressed wythe and 50 mm for a pre-stressed wythe. PCSPs are structurally classified into three main categories (Noridah, 2010).

i. Composite section

This section is analyzed, designed, detailed, and fabricated in a factory to ensure that the two concrete wythes that make up a PCSP act integrally to resist applied load. The overall thickness of a panel acts as a single unit by providing a full shear connector between the wythes to allow sufficient strength capacity to transfer longitudinal shear and bending moment. In this way, flexural strain is distributed in the cross section of the panel, as shown in Figure 1.2 (a).

ii. Semi-composite section

This section is analyzed, designed, detailed, and manufactured as a partial composite during stripping, shipping, and assembling. In addition, it functions as a non-composite system for in-place loads. In practice, a sufficient shear connector is recommended to enhance the combination between certain types of materials and the transfer of shear forces during handling. Such bond is designed for the short term. The flexural strain distribution in the cross section of the panel is depicted in Figure 1.2 (b).

iii. Non-composite section

The non-composite section is analyzed, designed, detailed, and manufactured in a factory to ensure that the wythes can act separately even without the ability to transfer longitudinal shear forces. In the general design of structural and non-structural wythes, the latter is thinner than the former. Therefore, almost 50% of shear and bending moment can be resisted (Figure 1.2 (c)).

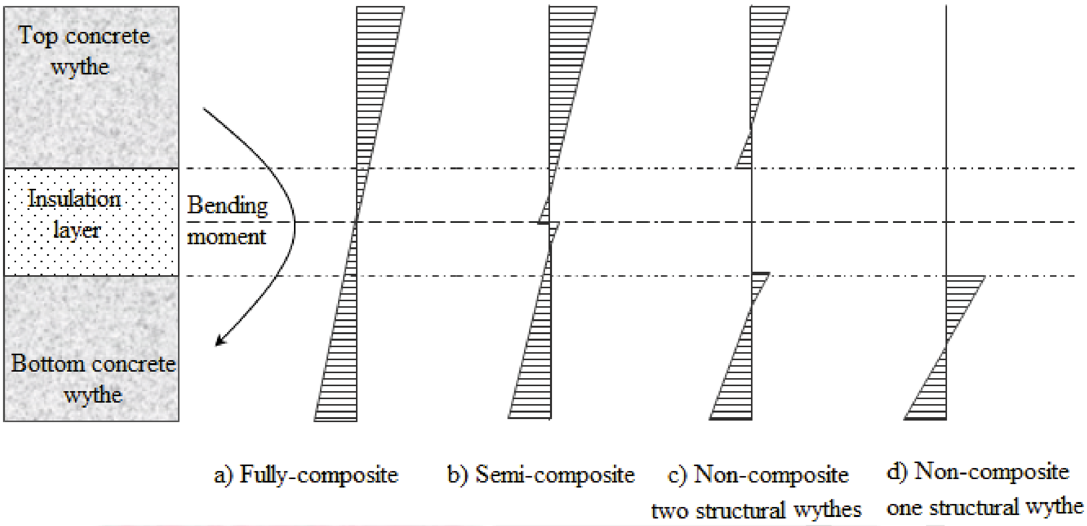

Figure 1.2: Strain distribution in the PCSP caused by bending

1.3 Foamed concrete and relevance

Foamed Concrete (FC) is widely used, especially in western countries. The United States uses FC in an increasing number of applications, such as cast-in-place roof insulation, bridge abutment, trench reinstatement, non- and semi-structural wall systems, and void filling in geotechnical engineering (Mugahed *et al.* 2015). The performance of FC basically depends on its compressive strength, which is usually influenced by several characteristics, including density, moisture content, age, curing condition, sand and cement type, and the volume and type of the chemical foam agent used (Norlia *et al.* 2013). Moreover, the tensile strength of FC is controlled by curing conditions of up to 25% of its compressive strength and 0.1% of the strain at the time of rupture. Yet, its shear strength is close to 10% of its compressive strength. The structural density of FC is also limited between 1440 and 1850 kg/m^3 (Ramamurthy *et al.* 2009). Recently, construction industries have been inclined to apply an economical solution that can produce a viable product, such as FC with several unique features. Structural FC is primarily used to reduce the dead load of a building and provide the most efficient strength-to-weight ratio in structural elements (Noridah, 2010). Weight reduction results in easy construction and less used equipment such as crane and other facilities, thus, overall costs are reduced and construction quality is maintained (Yavuz *et al*. 2013).

1.4 Precast foamed concrete sandwich panel

The Precast Foamed Concrete Sandwich Panel (PFCSP) is a structure with an insulated and layered system. PFCSP is composed of external structural FC wythes that is sandwiched with a polystyrene as an insulation layer with a high thermal insulation of 0.07 K/m.w and a low density of 16.5 kg/m^3. The three layers act integrally via a proper connection established through continuous steel truss-shaped shear connectors. PFCSP is an alternative system developed to replace the conventional reinforced concrete components for both load bearing wall and floor slab elements. FC is used as a main lightweight material chosen to cast PFCSP. Structural FC achieved the desired strength and reducing the total dead load relative to traditional concrete. It also exhibited ideal strength–weight characteristic. The reduced total dead load encourages a decrease in foundation size and facilitates transportation and operation. The use of cranes in assembling is also minimized. Hence, the overall construction cost can be reduced (Yavuz *et al*. 2013). In this regard, PFCSP is considered as one of the valuable contributions of structural researchers to the resolution of the problem faced by foundation engineers in providing enough bearing capacity foundation that can carry the overall dead load of building superstructures in grounds made unstable by peat soil. Recently, the development of lightweight concrete sandwich panels has increased in construction industries worldwide (Noridah, 2010). PFCSP is effective in certain aspects, such as in terms of the weight–strength ratio based on full-scale architectural and structural considerations. Many engineers and designers are unlikely to focus on the structural applications of FC (Bing, 2011). Therefore, further research on the types of lightweight concrete sandwich panels used as outer skins is necessary (Suryani and Mohamad 2012). The present study focused on PFCSP in structural engineering, including their strength, integrity, and self-weight reduction and enhanced the structural composite performance by proposing a sufficient number, arrangement, and the orientation of shear connectors used. Also, it reduced the self-weight of PFCSP by about 15-20% by using the FC compared to the current sandwich panel and at least by 20% through the reduction in the design geometry as a sandwich built-up, compared to RC applications. The feasible structural strength characteristics of PFCSPs under axial, in-plane shear, and out-of-plane loads with structural FC wythes are comprehensively investigated, and the degree of composite behavior is measured. The structural behaviors related to PFCSPs and their functional aspects in the load-bearing system of a low-rise residential building are also investigated. The suitability of employing PFCSPs as a slab element is then investigated.

1.4.1 Characteristics, significance, and attributes of PFCSPs

On the basis of previous studies, PCSP is thermally efficient systems that can reduce energy cost for air conditioning systems by nearly 44% as well as 20% in overall cost when compared with framed walls (Gleich, 2007). Also, the use of FC in the production of PFCSP has further improved thermal insulation performance (Nooraini *et al.* 2009). The FC applications can achieve a high rate of sound absorption, which could be 10 times higher than that of dense concrete (Jones and McCarthy, 2003). Existing studies indicate that FC exhibits an acceptable fire resistance compared with normal concrete because of the presence of closed-cell structures formulated in FC mass (Vilches, 2012). The demand for the construction of precast sandwich composites has greatly increased because of their easy installation and fast construction.

With consideration of the above, the present study has significances as listed below.

i. To develop a potential structural sandwich panel system by integrating FC to produce PFCSPs for bearing wall and flooring system components and thereby promote the quality of construction system.
ii. To predict the structural acceptance of PFCSPs on the basis of an experimental investigation, an analytical study, and theory rooted in the principle of reinforced concrete solid applications.
iii. To present the simplicity and practicality of commercially fabricated panels with lightweight materials for industrialization and marketing at the national and international levels and to consequently reduce the obstacles faced by low-income earners in owning affordable and quality housing.

The three attributes involved to validate the IBS for construction are as follows:

iv. IBS must satisfy all structural engineering requirements, such as strength and integrity, under applied loads for multi-storey buildings.
v. IBS must maintain its economic value in terms of cost and design quality relative to traditional systems as well as the speed of construction.
vi. IBS must reveal superior material properties and thermal performance in comparison with traditional systems.

The present study aims to improve structural efficiency of PFCSPs by reducing self-weight, and performance enhancement of composite structures through the use of a proper orientation of shear connectors with a sufficient number, which leads to affordable quality design components for housing construction.

1.5 Problem statement

Housing remains a major challenge for construction industries worldwide, particularly in developing countries, due to the financial constraints and inappropriate technologies (Benayoune, 2003; Noridah, 2010; Nawi *et al.* 2014). The problem is further compounded by the rapid population increase, the lack of access to suitable areas or lands worthy of investment for the construction of residential buildings, and the demands for improved quality of life (Nawi *et al.* 2012). Responding to this challenge using traditional building construction systems is not easy, and hence, requires meeting the demand for affordable housing within a short time while preserving construction quality and reduces cost (9th Malaysia Plan, Nawi *et al.* 2011, Samsudin and Mohamad, 2013).

The current precast concrete panels behaves in a semi-composite manner due to factors such as number, spacing, arrangement, size of diameter, material of fabrication and orientation of the shear connector provided (Benayoune *et al.* 2008; Noridah *et al.* 2011; Gara *et al.* 2012; Noridah *et al.* 2014). Also, the design geometry of steel truss-shaped shear connector is reported the most effective connector used to increase the percentage of composite action (Farah, 2002; Benayoune et al. 2008; Noridah, 2010). Therefore, further study to improve the composite performance of PCSP by increasing the number of shear connectors via reducing spacing and making a proper arrangement and orientation, is highly needed. Many researchers conducted comprehensive studies on PCSP under different loadings, but no solid conclusions were drawn, thus, further studies with different slenderness ratio (H/t) and aspect ratio (L/d), adopting a full-scale experimental design sections in order to determine structural performance are required (Noridah et al. 2014; Joseph et al. 2015; Ukanwa et al. 2015).

However, precast concrete structures are commonly fabricated with conventional materials and thus result in heavy systems. Hence, the reduction of PCSP self-weight becomes highly imperative. Reportedly, the self-weight of a slab contributes to 40%–60% of the total dead load of a residential building structure (Yavuz et al. 2013). Therefore, a reduction of nearly 10% in the self-weight of a floor slab may lead to a 5% reduction in the self-weight of an entire building (Chopra, 1980). Also, many researchers have used lightweight concrete with non-structural grades limited to 17 MPa, to develop sandwich panels integrated by designing normal concrete caps at both ends in other to reduce early splitting failure (Memon et al. 2007; Sulaiman et al. 2009; Noridah, 2010; Noridah et al. 2011; Suryani and Mohamad 2012). Also, FC has the potential to be used for structural applications (Mindess, 2014). Therefore, further researches are extremely needed to obtain a potential and an alternative structural lightweight concrete composite system. Furthermore, the composite behavior of PCSP through experimental tests revealed slightly discontinued which may be due to inefficiency of the shear connector used (Noridah et al. 2014) or slippage of slippage inside the concrete wythes or because of debonding between reinforcement bars and shear connectors or less bounding between steel and concrete (Benayoune et al. 2008; Noridah, 2010). Though, there seems to be inadequate knowledge about nonlinear finite element analysis models for a full scale PCSP under different imposed loading conditions to further study structural performance (Kabir et al. 2005; Noridah et al. 2011; Gara et al. 2012; Ukanwa et al. 2015; Joseph et al. 2015). Thus, extending FEA simulation is required for the purpose of verification of the experimental results.

The hypotheses of the study are; 1) the use of FC in the production of PFCSP is a potential material in maintaining strength-to-weight characteristic and could further possibly reduce the self-weight of PFCSP components, 2) the development of a load-bearing PFCSP wall is applicable and safe in the construction of a low-rise residential building, 3) the assessment in the use of PFCSP as a slab has the possibility to replace the conventional reinforced concrete solid slab, and 4), a semi-empirical equation can be proposed on the basis of reinforced concrete solid wall principle, in order to predict the ultimate bearing strength capacity of the developed PFCSPs.

1.6 Objectives of the study

The objectives of this study are briefly listed as follows:

1. To develop a PFCSP that can serve as a load-bearing wall and a flooring element. Further, to determine the properties of FC for use in the production of PFCSP.
2. To study the structural behavior of a PFCSP wall under axial and in-plane shear load tests.
3. To determine the structural behavior of a PFCSP slab on the basis of experimental tests and theoretical analysis includes the extremes of fully composite and non-composite actions.
4. To analyse the structural behavior of PFCSPs using linear and non-linear FEA models and to compare the results with the experimental test results and reinforced concrete solid application principles.

1.7 Scope, relevance and limitations of the study

This research covers experimental work on load bearing PFCSP walls and PFCSP slabs produced from foamed concrete of average compressive strength of 24.83 and 25.73 MPa at 28 days, respectively, in order to develop a lightweight structural element. The experimental includes trial mix to determine the basic properties of the FC and determine the sufficient density for the required compressive strength. The mix design of FC was in line with the British Cement Association. The desired FC with a sufficient strength and density was obtained through a first trial mixing of FC and shown to fulfill the structural requirements for use in the production of PFCSP. However, the foamed concrete was developed from fine natural sand with maximum aggregate size of 2 mm. A protein based foam solution was used in the foaming process using a portable high-expansion foam generator.

Further, welded-wire mesh size of 6 mm-diameter deformed bars with 100 mm × 100 mm openings was used as reinforcement in each wythe in line with the provision of ACI 318. More so, research has shown that reinforcement size does not have significant effect of the strength of the wall or slab, particularly, transverse reinforcements. Hence, the most economical size of 6 mm-diameter was chosen. The spacing was chosen on the basis of not more than twice the thickness of the wythes as specify in ACI 318-89. Five steel truss-shaped shear connector of 6 mm-diameter round bars were installed running along the span of the panel, tying both concrete wythes together to achieve a full composite action. Polystyrene thickness of 25 to 65 mm was used as insulator in the sandwich system. The thickness was chosen based on the recommendation of PCI standard that the thickness of insulator should not be less than 20 mm.

The wall specimen size between 1750 to 3000 mm was investigated for height variation. The height of 3000 mm was chosen based on the existing height of buildings around Asia and other parts of the world; in addition, the thicknesses of the panels were selected based on the recommendation of PCI standard. Hence, the need to carry out to full scale slabs and wall with full composite behavior. This is achieved by increasing the number of shear connectors with proper orientation in one direction because it can also facilitate in inserting the insulation material between shear connectors during the practical production. Also, thickness variation between 105 to 225 mm in the wall specimens was undertaken on the same wall heights aforementioned. Axial and in-plane shear load test were carried out the wall produced and in cases, height and thickness variations were investigated. This experiment is unlike the previous works that are mostly in small sizes while generalizing results for all elements sizes.

Slabs of 2750, 3000, 3250, 3500, 3750, and 4000 mm span were produced and tested under out-of-plane load. Two sets of thicknesses of 150 and 170 mm were fabricated at constant width of 1200 mm. The results were compared with the theoretical analysis includes the extremes of fully composite and non-composite actions, the FEA models data and the classical elastic theory calculation values.

A total of eighty (18) number of walls and twelve (12) slabs were produced making a total of thirty (30) PFCSP walls and slabs, plus three (3) PCSPs with one panel was set as control for each typical test conducted. Finite Element software (FEA) was used to study the structural behavior of the PFCSPs under different applied loads that are similar to the experimental test conditions. Full-scale laboratory tests under purely axial, in-plane shear, and out-of-plane loads were robustly verified all the walls and slabs produced with the ACI 318-89 design equation for reinforced concrete solid applications and other empirical formulas developed by previous researchers. A semi-empirical equation for load bearing wall was proposed under principle of reinforced concrete solid wall, in order to predict the ultimate bearing strength capacity of the developed PFCSPs.

The limitations of the study are to improve structural composite performance and reduce the self-weight of the PFCSP. In the conclusion, the study mainly aimed to obtain a lightweight PFCSP system component to use in the construction of a low-rise residential building worldwide.

1.8 Thesis layout

This thesis comprises seven chapters, including Chapter I. The contents of Chapters II to VII are described below.

Chapter II

This chapter introduces the relevant literature review focused on the IBS and the structural performance of PCSPs. It briefly presents the theoretical studies on solid RC wall system components and the experimental investigations that were carried out using laboratory testing and analytical and numerical approaches with the goal of validating the potential use of such materials in actual construction. The uses, properties, and applications of FC in PFCSP production are also concisely reviewed. Furthermore, the lightweight applications of sandwich panels as well as existing FEA studies are included in the thesis.

Chapter III

This chapter presents the methodology used to perform the experimental investigations, the theoretical computations, and the analytical study aimed at achieving the objectives stated. The material, specimen fabrication, and test setup and procedures are explained in detail. The classical study approach, theoretical calculation expressions, and FEA models of the PFCSP are also discussed.

Chapter IV

This chapter covers the discussion of structural FC properties and the observations made on the data obtained from the experimental tests under axial load and those from the adopted FEA models. The related parameters are the PFCSP wall bearing capacity, load–deflection profiles, load–strain relationships, influence of slenderness ratio, composite behavior, failure modalities, cracking patterns, and propagations. The experiment data also validate the structural performance of sandwich wall panels by associating their characteristics with those of the FEA models under axial load application, including their buckling behavior. Furthermore, the theoretical study is conducted with the aid of the theoretical expressions obtained from existing research and design codes. The theoretical results are then compared with the experimental results and the FEA model data.

Chapter V

This chapter presents the data obtained from the experimental investigations under in-plane shear loads, including those from the analytical study using the FEA models. The associated studies include the PFCSP in-plane wall strength, load–

deflection profiles, load–strain relationships, influence of slenderness ratio, failure modalities, shear cracking patterns, and propagations. The applicability of the adopted FEA model data is also presented to verify the experiment results obtained. The ultimate values obtained via the ACI design codes and expressions of previous researchers are compared with the test results and FEA model data. The comparison reveals a substantial agreement between the results.

Chapter VI

This chapter provides the results obtained from the experiment and the data obtained from the 2D FEA models, which functioned as one-way slabs under out-of-plane loads. The structural performance of PFCSPs is also studied to investigate the suitability of PFCSP slabs in residential housing. The observations cover the PFCSP ultimate strength capacity, load–deflection profiles, strain distribution, load–strain relationships, influence of aspect ratios, calculation of composite and non-composite extremes, degree of composite actions, load of failure, and flexural cracking. In addition, a parametric study is conducted to identify the number of composite actions achieved. The theoretical analyses of the axial shear forces on the truss connector legs were determined. The results obtained from the experimental tests are compared with the 2D FEA model data, and a significant agreement between the two sets of results is determined.

Chapter VII

This chapter presents the summary and conclusions of the major findings of this study. Some recommendations for future research are also provided.

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