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STRUCTURAL BEHAVIOUR OF PRECAST CONCRETE SANDWICH PANEL WITH HIGH THERMAL EFFICIENCY

SANI MOHAMMED BIDA

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By

SANI MOHAMMED BIDA

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

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DEDICATION

This thesis is dedicated to my precious mum and wife for their supports, encouragement and prayers.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman: **Assoc. Prof. Farah Nora Aznieta Binti Abd.Aziz, PhD**
Faculty: **Engineering**

Malaysian Government has targeted the year 2020 for full implementation for energy efficiency in buildings known as Green Building. In line with this perspective, this research aims to develop a thermally efficient and structurally acceptable precast concrete sandwich panels (PCSP) for structural applications. In order to achieve the aims, four objectives are outlined to determine the thermal and structural performance of staggered shear connectors. The staggered shear connector is a method used to avoid thermal bridges between layers. In this research, PCSP is designed with staggered shear connection spaced at 200, 300 and 400 mm on each concrete layers. While the control panel is designed with a direct shear connection at 200 mm. Four panels of 500mm x 500mm and 150mm thick are subjected to Hot Box Test to determine the thermal performance. While for structural performance, four (4) number of a full-scale panel of size 2500mm x 1650mm x 150mm are subjected to flexural test and another four (4) of 3000mm x 1650mm x 150mm size for axial load tests. These experimental results are validated by numerical analysis using the finite element method (FEM). In addition, an empirical equation of axial load capacity of the reinforced concrete wall was modified to determine the PCSP capacity. The hot box test result shows that thermal efficiency of the PCSP with staggered shear connectors increases with increase in spacing. The PCSP with 400 mm staggered shear connectors indicate the best thermal efficiency with a thermal resistance (R-value) of 2.48 m^2K/W. The R-value is higher than the maximum value recorded in the literature. The thermal performance was verified by FEA which shows less than 5% error coupled with a precise prediction of isothermal flux lines behaviour. The structural performance of PCSP under flexural loading showed that all PCSP with staggered shear connector achieved full compositeness with no debonding failure observed. The PCSP panel with a staggered shear connector at 300mm is capable of sustaining the axial capacity for five (5) storey load. However, beyond 300 mm staggered shear connector, the PCSP failed due to bucking. The experimental results were verified by FEA with about 4% and 15% error for the flexural and axial loadings, respectively. The empirical equation of axial load capacity of the reinforced concrete wall has overestimated the ultimate load capacity of PCSP. Therefore, the equation is subjected to statistical analysis using particle swarm optimization technique (PSO) by taking into

consideration the effect of insulation and shear connection in PCSP. The modified equation has successfully predicted load capacity of PCSP with high accuracy. The result was achieved with objective function (MAE) at swarm 30 with minimum iteration and *CoV* value of 10%. In conclusion, the PCSP with 300mm staggered shear connectors has met the energy efficiency requirement for sustainable buildings i.e. thermally efficient with excellent structural performance in both axial and flexural behaviour. These results proved that better thermal resistant and structural performance of PCSP can be achieved using conventional steel and concrete materials using staggered thermal path approach. Hopefully, the output of this research will help designers; both architects and engineers to choose PCSP wall to provide better thermal resistance and load bearing structural panels toward green and sustainable buildings.

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

KELAKUAN STRUKTUR PANEL APIT KONKRIT PRATUANG BERKECEKAPAN HABA TINGGI

Oleh

SANI MOHAMMED BIDA

Oktober 2018

Pengerusi: **Prof. Madya Farah Nora Aznieta Binti Abd.Aziz, PhD**
Fakulti: **Kejuruteraan**

Kerajaan Malaysia mensasarkan tahun 2020 untuk perlaksanakan sepenuhnya kecekapan tenaga di bangunan yang dikenali sebagai Bangunan Hijau. Sejajar dengan perspektif ini, kajian ini bertujuan untuk membangunkan panel apit konkrit pratuang (PCSP) yang berkecekapan haba dan strukturnya diterima untuk aplikasi struktur. Bagi mencapai matlamat penyelidikan ini, empat objektif dinyatakan untuk mengenalpasti kemampuan haba dan struktur bagi sambungan ricih berperingkat panel. Metod sambungan ricih berperingkat ini adalah untuk mengelakkan jambatan haba antara lapisan. Dalam kajian ini, PCSP direka dengan sambungan ricih berperingkat pada jarak 200, 300 dan 400 mm pada setiap lapisan. Manakala, panel kawalan direka dengan sambungan ricih langsung pada jarak 200 mm. Empat panel bersaiz 500mm x 500mm dan ketebalan 150mm dikenakan ujian kotak panas untuk mengenalpasti kemampuan habanya. Manakala untuk kemampuan struktur, empat (4) jumlah panel berskala penuh bersaiz 2500mm x 1650mm x 150mm dikenakan ujian lenturan dan empat (4) lagi panel persaiz 300mm x 1650mm x 150mm dikenakan ujian paksi. Keputusan ujian ini telah divarifikasi oleh analisis berangka yang menggunakan perisian metod elemen terhad (FEM). Tambahan pula, persamaan empirikal bagi kapasiti beban paksi bagi dinding konkrit bertetulang diubahsuai untuk mendapatkan kapasiti PCSP. Keputusan ujian kotak panas mendapati kecekapan haba bagi PCSP dengan sambungan ricih bertingkat bertambah dengan pertambahan jarak sambungan ricih tersebut. Panel PCSP dengan sambungan ricih jarak 400 mm mencapai kecekapan haba terbaik dengan rintangan haba (nilai R)(sebanyak 2.48 m^2K/W. Nilai R ini jauh lebih tinggi daripada yang direkodkan dalam kajian terdahulu. Prestasi termal ini telah diverifikasi menggunakan perisian FEA dengan ralat kurang daripada 5% dan meramalkan kelakuan lilitan fluks isoterma dengan tepat. Perlakuan struktur PCSP di bawah beban lenturan menunjukkan bahawa semua PCSP dengan sambungan ricih bertingkat mencapai kapasiti komposit penuh dengan tiada kegagalan sambungan permukaan yang diperhatikan. Panel PCSP dengan sambungan ricih bertingkat 300 mm menunjukkan kapasiti paksi mampu mencapai beban bangunan lima (5) tingkat, namun, bagi PCSP bersambungan lebih dari 300mm, kegagalan lenturan dikenalpasti. Keputusan hasil ujikaji atau eksperimen divarifikasi oleh FEA dengan ralat lebih kurang 4% dan 15% untuk beban lenturan dan paksi. Persamaan empirikal bagi

kapasiti beban paksi bagi dinding konkrit bertetulang telah terlebih anggar kapasiti muktamad PCSP. Oleh itu, persamaan empirikal tersebut telah dikenakan analisis statistik menggunakan teknik pengoptimuman swarm partikel (PSO) dengan mengambilkira kesan lapisan insulasi dan sambungan ricih. Persamaan yang telah diubahsuai telah berjaya menganggarkan kapasiti muktamat beban PCSP dengan ketepatan yang tinggi. Hasilnya dicapai dengan fungsi objektif (MAE) pada kumpulan 30 dengan pengulangan minimum dan nilai CoV 10%. Sebagai kesimpulan, PCSP dengan sambungan ricih 300mm telah berjaya memenuhi keperluan kecekapan tenaga untuk bangunan lestari i.e. kecekapan haba, dengan pencapaian struktur yang cemerlang didalam perlakuan paksi dan lenturan. Keputusan ini membuktikan ketahanan haba dan pencapaian struktur yang lebih baik mampu dicapai oleh PCSP yang menggunakan tetulang dan konkrit konvensional dengan pendekatan jambatan haba bertingkat. Mudah-mudahan, hasil kajian ini akan membantu pereka bentuk seni bina dan jurutera untuk memilih PCSP sebagai dinding yang memberikan ketahanan haba dan struktur penanggung beban yang lebih baik ke arah bangunan hijau dan lestari.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Farah Nora Aznieta Binti Abd.Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Saleh Jaafar, PhD
Professor, Dato. Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Farzad Hejazi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Nabilah Abu Bakar, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Name and Matric No.: Sani Mohammed Bida (GS45203)

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Signature: __________________________
Name of Chairman of Supervisory Committee: Associate Professor Dr Farah Nora Aznieta Binti Abd.Aziz

Signature: __________________________
Name of Member of Supervisory Committee: Professor Dato Dr Ir Mohd Saleh Jaafar

Signature: __________________________
Name of Member of Supervisory Committee: Associate Professor Dr Farzad Hejazi

Signature: __________________________
Name of Member of Supervisory Committee: Dr Nabilah Abu Bakar

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LIST OF ABBREVIATIONS

q	Heat flux (W/m^2)
R	Thermal resistance (m2 K/W)
t	Thickness of panel
T	average temperature (K)
U	thermal transmittance (W/m^2/K)
DOE	Department of Energy
EPBD	Directive on Energy Performance of Buildings
EU	European Union
Exp	Experimental
FEA	Finite Element Analysis
FRP	Fibre Reinforced Polymer
GBI	Green Building Index
HB	HotBox test
HRC	Housing Research Centre
PCSP	Precast concrete sandwich panel
P0	Control panel
P2	Panel with 200 mm connector spacing
P3	Panel with 300 mm connector spacing
P4	Panel with 400 mm connector spacing
TC	Cold surface
TH	Hot surface
T1_Num	Hot sample surface Numerical
T2_Num	Cold sample surface Numerical
T1_Exp	Hot sample surface Experimental
T2_Exp	Cold sample surface Experimental
US	United State
nZEB	near Zero energy buildings

CHAPTER 1

INTRODUCTION

1.1 Background

Innovative technology is required in the construction industry in order to provide more sustainable buildings that are practicable in the field. Therefore, precast component are more preferable to conventional building construction, which can shortened construction period without sacrificing quality of the product. In addition, the offsite or factory manufactured components has reduced the cost of production due to it shorten construction time and less labour.

In Malaysia, precast system is also known as Industrialised Building Systems (IBS) that is implemented in two stages, namely: (1) productions of modular parts in a yard/factory located near the site or transported and, (2) assemble for erection at the construction sites at in-situ position. IBS received greater attention after the Second World War particularly in the war-devastated countries due to rapid population growth, but its development and acceptance especially in Asia is still low. Beside Europe and USA, conventional construction technique is still predominant in most countries in Asia including Malaysia (Thanoon et al., 2003; Mydin et al., 2014). Survey conducted by Construction Industry Development Board (CIDB) Malaysia revealed that the adoption level of IBS in Malaysia stands at about 15% after over 40 years of initiation (Nawi et al., 2011). Hence, it is necessary for researchers in Malaysia to continue doing research on IBS development, compatibility and practicality to the local environment.

Apart from IBS, the need to produce sustainable buildings is growing. Sustainable building, also refer to as green building is a design philosophy that emphases on increasing efficiency in the use of resources such as energy, water, and materials in buildings. It reduces possible negative impacts on human life and the environment during it intended lifecycle through design, construction, operation and maintenance (Chua and Oh, 2011). Therefore, the most important sustainability feature in this research is the ability to use less energy during the intended design lifecycle of buildings. In tropical countries, most buildings use air-conditioners to control the temperature while, in Polar Regions, heaters are used that is subsequently becoming unsustainable.

Recently, global interest in energy conservation due to sustainability issues has called for a renewed demand for energy efficiency in building components. Because, substantial amount of thermal (heat) transfer through convection or radiation from external surrounding of the building into the inner part, thus, requiring power for cooling or heating (Demirboğa, 2003). In America, a significant share of energy consumption comes from housing with about 50-70% coming from heating and cooling or air-conditioning (Al-Homoud, 2005). In Europe, buildings account for about 30% of energy use which could be more in arid and semi-arid region of the word. In China, heating or cooling energy requirement in buildings account for about 15% of the total energy and is increasing by the day (Jiang and Wu, 2010; Zeng et al., 2011). Generally, buildings account for about 25–40% of total energy consumption which is mostly due to space heating or air-conditioning (Široký et al., 2011; Zeng et al., 2011; Robinson et al., 2017). So, this has become a challenging phenomenon with far-reaching consequences on the environment.

Therefore, in an effort to conserve the energy, various governments' agencies have been working vigorously toward zero energy buildings (ZEBs) which is becoming part of energy policy in several countries; in the Europe, EU Directive on Energy Performance of Buildings (EPBD) was set to the year 2020 in which all new buildings are expected to comply with "nearly zero energy buildings" (Sartori et al., 2012). In the United States, US Department of Energy (DOE) unveiled its strategic master plan toward "marketable zero energy homes in the year 2020 and commercial zero energy buildings in 2025", while in Malaysia, the government introduced Green Building Index (GBI) in 2009 whose target is to achieve 100 green rated factories and more in buildings by the year 2020 (Chua and Oh, 2011). Similar policies have been enacted in many countries as shown in Table 1.1.

Therefore, to achieve this targets, a more practical and sustainable approach through minimization of thermal (heat) transfer between outside and inner parts of buildings such as the provision of insulation layer between the building components refer to as precast concrete sandwich panel (PCSP) could be a way out. This is consistent with the report by Gervásio et al. (2010), who highlighted that material and energy efficiency are the two main factors contributing to the building's sustainability. Therefore, optimization of energy use such as in heating and cooling during building's service period by introducing an insulation material into the building is one way of improving the energy efficiency in buildings.

Table 1.1: Countries with their green/sustainable building indicator programs

Country	Green Building Program	Year of Initiation	Achievement to date
Autralia	Green Star	2003	1900 Green rated projects
Brazil	Aqua/ LEED Brasil	2010	1,308 registered projects
Canada	LEED canada/Green Globes	2000	2576
China	GBAS	2006	-
Finland	PromisE	1998	-
France	HQE	1996	16000
Germany	DGNB	2007	2800 certificates
Hong Kong	HKBEAM	2009	Over 1000
India	Indian Green Building Council (IGBC)	2007	Over 4794 buildings
Indonesia	Indonesian Green building Council (Greenship)	2009	-
Italy	Protocollo Itaca	2000	-
Japan	CASBEE	2004	500 Over buildings
Korea	KGBC	2000	1786
Malaysia	Green Building Index (GBI)	2008	Over 300 projects
Mexico	LEED Mexico	2000	Over 94000
Netherlands	BREEAM Netherlands	-	-
New Zealand	Green Star NZ	2005	153 buildings
Portugal	Lider A	2005	
Singapore	Green Mark	2005	Over 360 projects
South Africa	Green Star SA	2007	-
United States	Build it Green/LEED/IGCC/	1993	-
United Kingdom	BREEAM	1990	-
United Arab Emirate	Estidama	2009	-
Jordan	EDAMA	2009	-
Czech Republic	SBToolCZ	2005	-

1.1.1 Precast Concrete Sandwich Panel

Generally, sandwich refers to the combination of different material together either in layers or as a matrix to form a composite. This approach can be implemented on various materials and systems depending on its intended application. Precast concrete sandwich panels (PCSP) are composite system that consists of two or more layers of concrete called wythes which are separated by layer of insulation as shown in Figure 1.1. The wythes are connected to each other to form an assembly system through steel connectors, concrete webs or a combination of both (Einea et al., 1991; Benayoune et al., 2006).

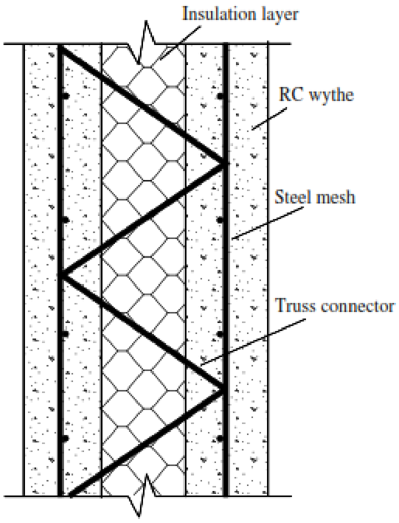

Figure 1.1: Section through Precast Concrete Sandwich Panel (Hamed, 2016)

The existing PCSPs are designed with continuous shear connection, which causes thermal bridges across the layers (wythes) as shown in Figure 1.1. The thermal bridge significantly reduces the thermal performance of PCSP system. Therefore, most research interest in PCSP have been focused on the use of alternative material such as fibre reinforced polymers (FRP) other than conventional steel as shear connectors to reduce the effect of thermal bridge. Some of the FRP materials used as shear connectors are carbon fibre reinforced polymers (CFRP) (Cho et al., 2010; Bunn, 2011; Frankl et al., 2011; Hodicky et al., 2014), Basalt fibre reinforced polymers (BFRP), Glass fibre reinforced polymers (GFRP) (Maximos et al., 2007; Pantelides et al., 2008; Seo et al., 2013; Woltman et al., 2013; Corradi et al., 2014; Choi et al., 2015; Kazem et al., 2015; Kim and You, 2015; Kang and Kim, 2016). However, these materials are expensive and will increase the cost of PCSP, coupled with structural effects such as high bond slip and high brittleness failure when used.

The continuous shear connection are still in use and most of the previous works reported are on the structural performance of the panel alone. The influence of certain parameters such as slenderness ratio and aspect ratio on structural performance have been established (Bush and Stine, 1994; Benayoune et al., 2006; Benayoune et al., 2007; Benayoune et al., 2008; Gara et al., 2012; Carbonari et al., 2013). However, more research works are needed in the area of shear connection design which affect both the thermal and the structural performance of PCSP system.

Besides changing the shear conenctor materials, effort has been made to improve the thermal performance of PCSP by replacing the concrete wythes with foamed concrete due to its low thermal conductivity (Mohamad et al., 2011; Mohamad and Hassan, 2013; Amran et al., 2016a; Amran et al., 2018). Foamed concrete is defined as a light cellular concrete produced from mixture of foaming agent in mortar which contains randomly distributed air voids and have a density range of 400–1850 kg/m^3 (Amran et al., 2015). This material result in a lightweight panels, but, is associated with structural effects such as crushing, sudden failure and high porosity which absorps water and reduce the thermal performance, that shows limited application particularly in weather exposed condition.

1.2 Problem Statement

In an effort to conserve the energy, various governments' agencies have been working tirelessly toward a more sustainable and energy efficient buildings (Wells et al., 2018). Currently, energy efficiency in buildings has formed part of legislation as policy in many countries including Malaysia (Zuo and Zhao, 2014). In particular, the Malaysian government has targeted the year 2020 as a dateline for any new building or buildings undergoing major repairs to satisfy energy performance requirement before approval (Chua and Oh, 2011). However, despite this target, most building construction in Malaysia are still predominantly conventional masonry walls and solid concrete panels. This building technology exhibit high thermal transmittance and conductivity (Soares et al., 2013).

In Malaysia a few agencies discussed on this issue, the Malaysian Government Green Building Index (GBI) master plan, which is given the responsibility to assess, certify, license and approve buildings that are deemed thermally efficient highlighted the needs of using green material and thermal efficient designs for buildings (GBI, 2018). Apart from that, the Malaysian Green Building Confederation has reported that after over 50 years of rapid industrialization with an annual growth of between 5% to 9%, most of the successes recorded are unsustainable, in another word, it require holistic sustainable approach especially in terms of thermal performance (MGBC, 2018). Furthermore, MS1525 (2014) was enacted to ensure energy sustainability in the building sector but did not mentioned on the thermal efficiency of sandwich panel.

According to Gervásio et al. (2010), the most sustainable way to develop thermally efficient building system is through the use of insulation material known as precast concrete sandwich panels (PCSP). These panels are more thermally efficient and are used as non-load bearing placed as partition walls (Losch et al., 2011). While, most building components used in Malaysia construction industry are slabs, beams and columns which are thermally inefficient (Mydin et al., 2014).

Development of load-bearing PCSP requires high level of shear connection which in turn reduce thermal performance (Benedetti et al., 2018). In Malaysia, load-bearing PCSP application mainly focuses on single and double storey buildings (Badir et al., 2002). However, the limited space in city centres and the need for urbanisation has called for high rise and structural buildings. Therefore, if structural building made of PCSP can be developed, the dreamed GBI master plan would easily be achieved. Therefore, the main component of PCSP that ensure load bearing capacity and composite action is the shear connectors and a concrete section that connect the two wythes together.

The most predominant shear connectors use in the existing PCSP are shear steel truss, double truss, bend up bars, hooks, pins and continuous truss shear connection (Naito et al., 2011). These connectors are continuously connected from layer or wythe to another through the insulation which causes thermal bridges and subsequently reduces the thermal performance of the panel (Tomlinson and Fam, 2015). Besides, according to Amran et al. (2015), when 0.08% of direct steel pin shear connection is used, thermal reduction of about 77% is observed. Hence, the need to avoid the effect of thermal bridges due to the shear connectors is necessary in PCSP in order to improve its thermal efficiency.

The other approach is the staggered thermal path reported by Zarr et al. (1987) who used timber PCSP and successfully increase the thermal efficiency of the panel. This concept was then repeated on three layered PCSP without shear connectors by (Lee and Pessiki, 2006)and reported better thermal efficiency than the conventional PCSP. Unfortunately, it is non-load bearing and un-economical due to excessive thickness and the production method is un-practicable.

Despite the type of shear connectors, its material will also influence the thermal and strength behaviour of PCSP. As mentioned earlier, many researches had been carried out using FRP material due to its lower thermal conductivity behaviour. This approach is considered to reduce the effect of thermal bridges. Significant improvements were recorded in terms of strength, but bond slip and brittle failure between the shear connectors and concrete were observed. This can be improved by providing thicker concrete wythes sections to enable sufficient embedment length of the shear connectors. However, the panel becomes heavier and leads to uneconomical section. Apart from that, FRP shear connectors failed in sandwich panels at strength far below its tensile capacity and in brittle mode making it less practical (Hodicky et al., 2014).

Another approach to improving the thermal performance of the PCSP is by replacing the concrete wythes with Foamed and/or Aerated concretes. Even though, the thermal properties are improved, a significant reduction in strength parameters coupled with the sudden crushing of the specimen has been recorded (Mohamad and Muhammad, 2011; Amran et al., 2016b). Moreover, this material absorbs much more water than the conventional concrete that contributes to its high thermal performance. According to Steiger and Hurd (1978), when a unit weight of concrete increase by 1% due to water absorption, the thermal conductivity increases by 5%, making porous materials like foamed concrete exhibit higher values of thermal conductivity.

Many investigations on PCSP under flexural tests, shear tests and tests under combined shear and flexure abound in the literature (Huanzhi et al., 2017). However, investigations on PCSP under axial load are limited due to the high capacity equipment required and the cost of building full-scale panels (Benayoune et al., 2007). Based on these works of literature, it is obvious that most of the existing PCSP are excellent in thermal efficiency when it is made for the non-load-bearing panel. But, when it is designed as load-bearing PCSP, the thermal efficiency need to be compensated in order to allow the strength of the PCSP to reached its load-bearing performance. Thus, this research is to study the load-bearing PCSP that will not compensate the thermal efficiency of the wall. Hence, the following research questions are highlighted:

1. Is the staggered thermal path method suitable for load-bearing PCSP?

2. If the thermal path method works, what is the appropriate spacing between the shear connectors that fulfilled the energy performance requirement as well as the structural performance?

3. What are the axial and flexural capacity of the load-bearing PCSP with different spacing of the connectors?

4. Is there any established equation to estimate the axial load capacity of PCSP?

1.3 Objectives

Based on the above-mentioned research questions, the aim of this research is to develop a thermally efficient load-bearing PCSP that satisfy both thermal and structural performances. To achieve this, the work tasks consists of four main objectives:

1. Three different shear connector spacing will be studied using staggered thermal path methods to determine the optimum thermal performance of PCSP and the results will then be verified using Finite Element Analysis (FEA) method.
2. To determine the structural performance of the proposed PCSP with staggered shear connectors when subjected to flexural and axial loads.
3. To verify the structural behaviour of the PCSP using Finite Element Analysis (FEA) method when subjected to flexural and axial loads.
4. To propose an empirical equation for axially loaded PCSP.

1.4 Scope and Limitation

This research covers experimental work, finite element modelling and empirical equation modelling on precast concrete sandwich panels. The experimental work involves thermal performance test, flexural test and axial load test. Each of the tests consists of four (4) PCSP. For the thermal test, the specimen size is 500 mm x 500 mm x 150 mm, while, for the flexural test is 2500 mm x 1650 mm x 150 mm and 3000 x 1650 x150 mm for the axial test. All the specimens are made from 40 MPa concrete strength and minimum reinforcements are provided. The shear connector studs are cast with mortar of 40 MPa. Three different staggered shear connector spacing is studied; 200mm, 300, and 400mm.

The scope of the thermal test covers PCSPs with staggered shear connectors and Foamed Putra Blocks and Mortar Putra Block for comparison purposes. The test specimen is limited to small-scale to accommodate the test set-up. The results are verified by Finite element Analysis (FEA) using COMSOL Multi-physics, a software to develop 3D-models for the thermal performance verification. In the numerical modelling, insulation of the boundary conditions was ensured using the default full-insulation settings of the software. While for the structural tests, specimens are different in size to accommodate the size limitation of the test frame. The numerical analysis using Abaqus CAE was used to validate the experimental results of both flexural and axial tests.

Since the theoretical equation regarding axial load capacity is scarce in literature, the existing equation for solid wall panel according to ACI 318-M (2011) is statistically modified using particle swarm optimization (PSO) method. This is done to incorporate the appropriate parameters to improve the equation for use in PCSP. The statistical analysis was carried out with the aid of MATLAB software using data obtained from experimental, FEA and literature. The PSO analysis takes into account two main parameters that influence the behaviour of the PCSP namely an insulation material and shear connection. The proposed equation is limited to estimation of axial load capacity for PCSP only.

1.5 Layout of Thesis

This section presents the layout of thesis and the content of each chapter.

Chapter one presents the background to the need for the new/modification of the existing precast concrete sandwich panels. The objectives, problem statement, scope and limitation of the research work are also presented.

Chapter two present the literature review on general precast concrete panels from the conventional precast normal weight walls to the current state of the art sandwich systems and the need to further modify the current systems toward sustainable and thermally efficient structural system.

Chapter three discusses in detail the experimental and FEA results obtained on the thermal (heat transfer) analysis of the proposed sandwich panels. The investigation include; material, methodology, experimental and FEA analysis and verification of the results.

Chapter four present the methodology used to carry out the experimental and FEA on the structural performance of the proposed PCSPs. The procedure employed and design approach used. Standard test methods adopted during the experiments are also presented. The methodology include experimental and numerical analysis used for the structural tests.

Chapter five presents the experimental results of the proposed panels under structural test (flexural and axial loadings). Also, failure patterns and load capacity of the panels are discussed in details.

Chapter six presents the FEA results of the proposed panels under structural test (flexural and axial loadings). Also, failure patterns and load capacity of the panels are discussed in details.

Chapter seven presents the analytical equation developed for the structural capacity of the panels under axial loading. The analytical equation is developed using Particle swarm Optimization Approach with the aid of MatLab software.

Chapter eight presents the discussion, conclusions and recommendations based on the results achieved. Recommendation for further investigation or action are proposed for continuous sustainable development.

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BIODATA OF STUDENT

Sani Mohammed Bida was born on the 25 December, 1979 in Bida Local Government of Niger State, Nigeria. He obtained his Bachelor's Degree in Civil Engineering (B. Eng) in 2005 from Bayero University Kano, Nigeria. He further obtained Master of Science in Structural Engineering from Universiti Putra Malaysia (UPM) in 2014. Thereafter, he began to pursuit his Doctor of Philosophy (PhD) in Structural Engineering in 2015. The author commenced his carrier as an engineer in the Ministry of Infrastructural Development, Niger State from 2007-2009 before he left for Federal Polytechnic Bida as Lecturer III. He has engaged in many activities professionally outside his work environment as Non-Governmental Organization (NGO). During this period, freelance structural designs are provided for communities as a social responsibility under the NGO.

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