STRUCTURAL BEHAVIOUR OF SLAB PANEL SYSTEM WITH EMBEDDED COLD-FORMED STEEL SKELETAL FRAME

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Dedicated to my beloved *family members*

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ABSTRACT

Precast lightweight slab panel system offers several advantages in construction industry, such as lightness, high strength-to-weight ratio, ease of transportation, saving of materials, and offers rapid construction. The design for the conventional reinforced concrete slab has been well established in current code of practice. There is, conversely, little scientific and technical information available for structural-grade lightweight foamed concrete (LFC) and lightweight slab panel design involving LFC incorporates with cold-formed steel (CFS) sections. This study aims to develop the design procedures for lightweight slab design, to find the optimal mix design for structural-grade LFC, to develop lightweight slab system that utilizing lightweight foamed concrete and cold-formed steel sections, to investigate the strength behaviour and to validate strength of the developed slab system via analytical and experimental investigation. Theoretical prediction on ultimate resistance and design procedure based on stress block method was deliberated. Trial mixes for structural-grade of LFC material are performed in accordance with Eurocode and ASTM to obtain the optimum mix design, with its mechanical properties are investigated. In addition, 16 full-scale slab specimens, incorporating different concrete mixes, reinforcement and CFS sections are prepared and tested to investigate the structural behaviour, such as ultimate load resistance, load-deflection profile, load-strain distributions and the failure modes. Theoretical validation for the experimental results was carried out. A design procedure for the lightweight slab panels is proposed for its possibility to be used. From the material study on LFC, an optimal mix design with cement-sand ratio of 3:1 and water-cement ratio of 0.49 was identified. Throughout the experimental investigation on full-scale slab, it was observed that all slab panels achieved the design resistance in accordance to Eurocode. Comparison is made between normal weight and lightweight slab panels revealed that the flexural resistance of lightweight slab panel is lower than that of normal weight slab panel. Nevertheless lightweight slab panel can save weight up to 47.1% relatively. The lightweight slab panels with single horizontal (SH) configuration showed the best performance. In addition, the results also exhibited that the flexural resistance of the slab panels increased as the effective steel area of cold-formed steel section increased. The convincing results concluded that the lightweight slab panel system incorporating lightweight foamed concrete (LFC) and cold-formed steel (CFS) skeletal frame is feasible to be used in construction industry.
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ABSTRAK

Sistem pratuang panel papak ringan menawarkan beberapa kelebihan dalam industri pembinaan, contohnya ringan, nisbah kekuatan-kepada-berat yang tinggi, kemudahan pengangkutan, penjimatan bahan, dan menawarkan pembinaan yang cepat. Reka bentuk untuk papak konkrit bertetulang konvensional telah mantap dalam kod amalan semasa. Sebaliknya, maklumat saintifik dan teknikal bagi konkrit ringan berbuih (LFC) untuk kegunaan struktur dan papak panel ringan yang melibatkan LFC menggabungkan dengan keluli tergelek sejuk (CFS) adalah masih kurang. Kajian ini bertujuan untuk merangka satu prosedur untuk reka bentuk papak ringan, mencari campuran optima bagi konkrit ringan berbuih untuk kegunaan struktur, membentuk sistem papak ringan yang menggunakan konkrit ringan berbuih dan keluli tergelek sejuk, mengkaji perlakuan kekuatan dan untuk mengesahkan kekuatan sistem papak yang dicadangkan melalui penyiasatan dan analisis eksperimen. Ramalan teori terhadap rintangan muktamad dan prosedur reka bentuk yang berdasarkan kaedah blok tegasan telah dibincangkan. Percubaan campuran untuk LFC gred struktur dilaksanakan mengikut panduan kepada Eurocode dan ASTM untuk mendapatkan campuran yang optima, dan sifat-sifat mekanikal dikaji. Di samping itu, 16 spesimen papak berskala penuh yang mengandungi campuran konkrit yang berbeza bersama dengan konfigurasi berbeza reka bentuk tetulang dan rangka CFS diuji untuk menyiasat kelakuan struktur, seperti beban rintangan muktamad, profil beban-pesongan, taburan beban terikan dan mod kegagalan. Pengesahan teori bagi keputusan ujikaji telah dibincang. Prosedur reka bentuk untuk panel papak ringan telah dicadangkan untuk kemungkinan digunakan. Daripada kajian bahan LFC, satu campuran optima telah dikenalpasti dengan nisbah simen-pasir 3:1 dan nisbah air-simen 0.49. Sepanjang siasatan uji kaji pada papak berskala penuh, telah diperhatikan bahawa semua panel papak mencapai ketahanan reka bentuk berpandukan kepada Eurocode. Perbandingan antara panel papak berkonkrit berat normal dan panel papak ringan mendedahkan bahawa rintangan lenturan panel papak ringan adalah lebih rendah daripada panel papak konkrit berat normal. Akan tetapi panel papak ringan boleh menjimat berat sebanyak 47.1%. Panel papak ringan dengan konfigurasi rangka keluli tergelek sejuk secara mendatar (SH) menunjukkan prestasi yang terbaik. Di samping itu, keputusan juga menunjukkan bahawa rintangan lenturan panel papak meningkat bersamaan dengan peningkatan luas permukaan efektif keluli tergelek sejuk. Kesimpulannya, sistem panel papak ringan dengan penggabungkan konkrit ringan berbuih (LFC) dan rangka tulang keluli tergelek sejuk (CFS) adalah sesuai digunakan dalam industri pembinaan.

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$\bar{b}$ - Appropriate width

α_{cc} - The coefficient taking account of long term effects on the compressive strength and of unfavourable effects resulting from the way the load apply.

$\sigma_{cr,s}$ - Elastic critical buckling stress

a - Depth of stress block

A_{g} - Area of the gross cross-section

$A_{\mathrm{g,sh}}$ - Value of A_{g} for a cross-section with sharp corners

A_{s} - Effective area

b - Width of element / slab width

b_{e1}, b_{e2} - Effective width of flange

b_{eff} - Effective width of an element

b_{p} , b_{p1} , b_{p2} - Flange width with mid-line dimension

$b_{\mathrm{p,i}}$ - Notional flat width of plane element *i* for a cross-section with sharp corners

c - Length of cold-formed steel lips

c_{eff} - Effective depth of lip

c_{p} - Lipped depth with mid-line dimension

d - Effective depth / depth of specimen at the point of fracture

D - Diameter of specimen

E - Young modulus

E_{c} - Elastic modulus of concrete

E_{s} - Elastic modulus of steel

f_c' - Mean compressive strength of concrete

F_{cc} - Resultant compressive force

f_{ck} - Concrete compressive strength

f_{ct} - Concrete splitting tensile strength
f_{ctm} - Mean axial tensile strength of concrete
f_{cu} - Concrete compressive strength
f_{r} - Mean flexural tensile strength of the concrete
F_{st} - Resultant tensile force
f_{u} - Ultimate strength
f_{y} - Yield strength
h - Depth of cold-formed steel web / depth of slab
$h_{1},h_{2},h_{\mathrm{e1}},h_{\mathrm{e2}}$ - Effective depth of web
h_{p} - Web depth with mid-line dimension
I_{g} - Second moment of area of the gross cross-section
$I_{\mathrm{g,sh}}$ - Value of I_{g} for a cross-section with sharp corners
I_{s} - Effective second moment area of the stiffener
I_{t} - Torsion constant
I_{w} - Warping constant
$I_{\mathrm{w,sh}}$ - Value of I_{w} for a cross-section with sharp corners
I_{y} - Second moment of area about major axis
i_{y} - Radius of gyration for major axis
I_{z} - Second moment of area about minor axis
i_{z} - Radius of gyration for minor axis
K - Spring stiffness
k_{σ} - Buckling factor
L - Length of slab
m - Number of plane elements / Modular ratio
M_{cr} - Cracking moment
M_{Ed} - Design resistance
M_{u} - Ultimate moment
$M_{\mathrm{u,exp}}$ - Experimental ultimate moment capacity
$M_{\mathrm{u,theo}}$ - Theoretical ultimate moment resistance
n - Number of curve elements
Ø - Angle between two plane elements
P - Total applied vertical load at failure
P_{cr} - Load at which the first concrete crack

P_s - Load at the allowable deflection

P_u - Ultimate load

r - Internal radius of cold-formed steel section

R - Modulus of rupture

r_j - Internal radius of curve element j

s - Lever arm between concrete compressive resistance and steel tensile resistance

S_c - Compressive strength

S_T - Indirect tensile strength

t - Thickness of cold-formed steel

v_c - Shear strength

W_y - Elastic section modulus for major axis

W_z - Elastic section modulus for minor axis

x - Neutral axis

y_gc - Centroid from web

y_lip - Centroid from lip

y_o - Shear centre from centroid

y_sc - Shear centre from web

y_t - Vertical distance of the extreme tension fibers from the neutral axis

z_c - Position of neutral axis regard to compression flange

$z_{g\mathrm{c}}$ - Centroid from flange

z_sc - Shear centre from flange

z_t - Position of neutral axis regard to tension flange

γ_c - Partial safety factor for concrete

γ_M0 - Partial safety factor for resistance of cross-sections whatever the class is

γ_s - Partial safety factor for steel

δ_u - Mid-span deflection at the ultimate load

$\mathrm{\varepsilon}$ - Coefficient depending on f_y / strain

ε_a - Longitudinal strain at the upper loading stress

ε_b - Longitudinal strain at the basic stress

ε_f - Strain upon failure

ε_{t1}	-	Transverse strain at the basic stress
ε_{t2}	-	Transverse strain at the upper loading stress
η	-	Factor defining the effective strength
$\lambda_{p,b}$, $\lambda_{p,c}$	-	Slenderness ratio
μ	-	Poisson's ratio
μ_t	-	Toughness
ρ	-	Reduction factor to allow for local buckling
σ	-	Maximum compressive strength
χ_d	-	Reduction factor
ψ	-	Stress ratio

LIST OF ABBREVIATIONS

AASTHO	-	American Association of State Highway and Transportation Officials
ACI	-	American Concrete Institute
ASTM	-	American Society for Testing and Materials
B	-	Buckle at failure part
BB	-	Buckle and break into half
BC	-	Partially encased composite I-girder with reinforcing bars were placed vertically and welded to the flange
BC-N	-	Partially encased composite I-girder with reinforcing bars were placed vertically and without welded to the flange
BCCFP	-	Bondek II/ cemboard composite floor panel
BPB	-	Buckle and partially break into half
BS	-	Conventional steel I-girder
BS EN 1991-1-1	-	Eurocode 1 Part 1-1:2002
BS EN 1992-1-1	-	Eurocode 2 Part 1-1:2004
BS EN 1993-1-3	-	Eurocode 3 Part 1-3:2006
BSI	-	British Standard Institution
C-S-H	-	Calcium-silicate-hydrate
CAN/CSA	-	Canadian Design Provisions
CFRP	-	Carbon fibre reinforced polymer
CFS	-	Cold-formed Steel Section
CH	-	Calcium hydroxide
DB	-	Distorsional buckling at failure part
DH	-	Double Horizontal C-channel section
DT	-	Displacement transducers
DV	-	Double Vertical C-channel section

EC3-1-3 - Eurocode 3 Part 1.3 (BS EN 1993-1-3: 2006)
FRC - Fibre Reinforced Concrete
FRP - Fibre Reinforced Polymer
GFRP - Glass Fibre Reinforced Polymer
GFRP-RCS - Glass fibre reinforced polymers reinforced concrete encased steel composite beam
HRS - Hot rolled steel section
IBS - Industrialised Building System
Inc - Inclinometer
JSCE - Japan Society of Civil Engineers
L & DB - Local and distorsional buckling at failure part
LAC - Lightweight aggregate concrete
LFC - Lightweight Foamed Concrete
LGSC - Light Gauge Steel Channel
LP - Fracture under loading point
LWCS - Lightweight conventional slab
LWSH - Lightweight slab with single horizontal CFS frame
LWSV - Lightweight slab with single vertical CFS frame
M - Base mix mortar
MS - Fracture at mid-span
NAHB - National Association of Home Builders
NWC - Normal Weight Concrete
NWCS - Normal weight conventional slab
NWDH - Normal weight slab with double horizontal CFS frame
NWDV - Normal weight slab with double vertical CFS frame
NWSH - Normal weight slab with single horizontal CFS frame
NWSV - Normal weight slab with single vertical CFS frame
OPC - Ordinary Portland cement
PI - Performance index
RC-SJ - Reinforced concrete encased steel joist beam
RCC - Roller Compacted Concrete
S - Flexural shear at support
S/C - Sand-cement Ratio

SC	-	The LFC mix with air dried and sieved sand that 100 % passing through 0.60 mm sieve opening
SCC	-	Self-compacting Concrete
SCS	-	Steel-concrete-steel
SH	-	Single Horizontal C-channel Section
SV	-	Single Vertical C-channel Section
T	-	Tearing of shear connector
U	-	Under-reinforced
UC	-	The LFC mix with raw sand that exposed to natural weathering
WM	-	Wire mesh
Y & B	-	BRC yield and break into half

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Concrete is a widely used construction material. Its popularity can be attributed to durability under hostile environments, ease with various different structures, such as dams, building, pavement, runways, tunnel, and bridge, and its relative economy and easy availability (Pillai and Menon, 2009). According to Li (2011), the worldwide production of concrete exceed that of steel by a factor of 10 in tonnage and by more than a factor of 30 in volume. Several types of concrete are available today, such as normal concrete, high strength concrete, lightweight concrete, self-compacting concrete, pervious concrete etc. The use of lightweight foamed concrete (LFC) gains its significant interest from the construction industry recently. LFC contains no coarse aggregate, but only fine sand, cement, water and foamed materials. With appropriate design, LFC with the wide range of densities from 300 kg/m^3 to 1900 kg/m^3 can be produced for the application as filler material, panels or block in civil engineering works. Besides that, LFC is good in thermal and acoustic insulation compared to normal concrete, which gives higher potential as walls and slabs in building construction.

Apart from concrete, steel also has been the prominent construction material in construction industry for long time. Due to the advancement of the technology and research in this field, new development in construction materials such as cold-formed steel sections has been effectively used for primary structural components in building construction. Cold-formed steel sections (CFS) has gains its popularity as purlins and rails, intermediate members between main structural frame and the corrugated roof or wall sheeting in buildings for farming and industrial use (Martin and Purkiss, 2008). In United states, over 100,000 houses per year used light steel framed, which proved of great user confident and excellent track record of cold-formed steel (Popoola *et al.*,2000). Cold-formed steel sections are fabricated by folding, press-braking of plates or cold-rolling of coils made from carbon steel. The steel section is relatively thin, typically with the thickness of 0.9 mm to 3.2 mm, and galvanized for corrosion protection (Dubina *et al.*, 2012; Lee *et al.*, 2014b). These sections may have the yield stress ranging from 250 MPa to 550 MPa. The main benefit of using cold-formed steel section is not only of its high strength-to-weight ratio but also its lightness, free individual shaping and beneficial geometrical features in relation to the cross-sectional area. According to Biegus (2006), cold-formed steel sections gain the advantages of reducing the metal content of 25 – 50% in comparison to hot rolled steel sections, 30% time saving for in-situ frame and total cost saving of 10 – 25%. Nevertheless, both concrete and steel has their own characteristic weakness. Therefore, the combination of the two materials can utilized the best part of its relatively characteristic and gives an optimum structural performance.

Reinforced concrete is considered as a composite material. Lower tensile strength and ductility of concrete will be counteracted by the addition of steel reinforcement that has higher tensile strength and ductility. Traditionally, reinforced concrete construction involved on-site casting or prefabricated concrete with the concrete strengthen by embedded and welded wire, steel reinforcement bar or steel mesh, fibre etc, making it to withstand the substantial stress. Relatively low strength-to-self weight ratio of reinforced concrete limits its design for large and long span members. However, the design has been well established and anchored in codes of practice (BSI, 2004a). Due to the Industrial Building System has now remerged worldwide into the 21st century as a sensible solution to improve construction image and performance, the use of pre-fabricated structures are recommended. Besides, 50% of multi-storey steel frame building used precast concrete slab (Way *et al.*, 2007).

Innovative concepts such as pre-stressed concrete and composite structure system are available in the local construction industry to overcome the limitation of reinforced concrete design. Generally, composite slab system refers to that the concrete slab acted along with cold-formed profile decking. This design had been well established and anchored in codes of practice (BSI, 2004b). Besides that, composite slab with steel decking had been proved as economic and lightweight structural building materials (Andrade *et al.*, 2004). Furthermore, the steel deck can act as the permanent formwork, provides a working area and the upper flange of the floor beams act as reinforcement in the tension zone of the slab (Seres and Dunai, 2011). Composite slab system is structurally efficient because it gives an optimum solution to the tensile resistance of steel and the compressive resistance of concrete. Thus, it gained recognition in North America especially for small commercial and residential building construction.

Nevertheless, these two types of construction- reinforced concrete slab and composite slab system are time consuming, as the concrete slab needs to be cast on-site and may introduce significant moisture into building (Wright *et al.*, 1989). Some quick installation slabs system needed to be introduce to overcome the problems faced by traditional concrete construction. This development will give tidier and cleaner site environment, minimized site wastage, save construction time and cost, accelerate sustainable building system and provide durable high quality control construction. In this research, some quick installation slab systems utilising CFS and LFC had been proposed. This research is to confirm that the proposed slab systems are feasible to use the in construction industry.

1.2 Problems statements

A slab structure consists 40% - 60% of total dead load and volume for an ordinary residential building (Yardim *et al.*, 2013). Reduction of 10% self-weight of slab may lead to 5% self-weight reduction of an entire building. The traditional cast in-situ slab system has heavy self-weight and is found to be challenging for long-span and large-scale construction project. This also leads to the needs of heavier equipment, transportation difficulties, expensive connection and joints solution. In order to have better structural performance and lower cost, the development of lightweight slab has become a critical need. Lightweight concrete such as lightweight foamed concrete (LFC) has been almost exclusively limited to non-structural application such as void filling, thermal insulation, acoustic damping, trench filling for reinstatement of roads and building blocks (Kearsley, 1999). Nevertheless, the compressive strength of LFC is exponentially correlated to density. A minimum strength of 17 MPa must achieve for LFC to perform for structural usage (Shetty, 2006). Besides that, the LFC has to maintain same characteristic with normal weight concrete but in low density. Furthermore, the air voids in LFC would lead the unprotected reinforcement susceptible to corrosion even when the external attack is not severe.

There are some lightweight slab systems from previous studies such as the one-way lightweight concrete slab by Kum et al. (2007), glass fiber reinforced polymer reinforced precast lightweight concrete panel by Liu and Pantelides (2013) and CFS partially embedded in concrete composite slab system by Lakkavalli (2005). These three studies have a similarity, i.e. the slab system casted used lightweight aggregate concrete. Besides that, the lightweight slab system studied by Lakkavalli (2005) was more probably made using cast in-situ composite slab system. Thus, as to the author knowledge, there is so far no study on the application of the hybrid system which combined the concept of reinforced concrete slab and composite slab. The prefabricated slab system incorporating CFS sections fully embedded as the skeletal in LFC has not been studied.

To date, the codes of practice (BSI, 2004a & BSI, 2004b) focus on analytical design of the conventional reinforced concrete slab and composite slab design. Currently, there is no standardized code of practise for LFC. BS EN 1992-1-1 (BSI, 2004a) mainly focuses on structural design using normal weight concrete and lightweight aggregate concrete. Nevertheless, the design mix procedure and materials properties of normal weight concrete could not be used for LFC (Kearsley, 2006). The detailed design method and requirements, especially for this new type of slab system has not been concluded. Hence, there is a need to carry out in-depth study for the performance of lightweight slab system that involved CFS section as the fully embedded reinforcement in LFC and developed the design procedures for such design.

1.3 Objectives

In order to answer the above problem statement, the objectives of research are as follow:

i. To develop the design procedures for lightweight slab design.
ii. To obtain the optimal mix designs of lightweight foamed concrete that fulfills the requirement for structural usage.
iii. To develop a lightweight slab system that utilizes lightweight foamed concrete and cold-formed steel sections.
iv. To investigate the strength behaviour and to validate the developed slab system via analytical and experimental investigation.

1.4 Scope of works

Lightweight materials such as lightweight foamed concrete (LFC) and cold-formed steel section (CFS) are used as the construction materials to produce a lightweight concrete slab system in this study. The CFS C-channel sections, with Grade 450 and dimension of 100 mm depth and 1.55 mm thickness, were fully embedded as the skeletal in the prefabricated slab system. There were two types of concrete used in this research, which were normal weight concrete (NWC) and LFC with Grade 25. As for lightweight foamed concrete, the density was targeted at 1700 kg/m^3. Besides that, there were four types of CFS skeletal in cooperating with both types of concrete were studied in this research. In depth, experimental investigations on its flexural behaviour is conducted. The aspects of bending resistance are compared between the theoretical and experimental approaches to validate the standardized design procedures.

Analytical investigations were carried out for better understanding on section properties and member capacities of single cold-formed steel sections. Detailed studies on the flexural design were made in a step-by-step calculation, to obtain the resistance of each slab configuration. Besides that, analytical comparisons between the slab configurations and changes of concrete types were made. Furthermore, comparison between the experimental and analytical investigations was made to lead to a conclusive design of the proposed slab system. The details of works involved are divided into several sections and organized into relevant chapters as described in Section 1.6.

The experimental programme includes: (1) Four series of lightweight foamed concrete trial mix to get the optimal mix design for lightweight slab system. (2) Sixteen full-scale slab panel consists of four different configurations of cold-formed steel skeletal to investigate the flexural behaviour of simply supported reinforced slabs under four-point load. The first set of ten slabs used normal weight concrete, while the second set of six slabs involved lightweight foamed concrete. (3) Control tests were carried out for both NWC and LFC and tensile coupon tests for CFS sections to measure the actual material properties.

1.5 Significant of study

As discussed previously, most of the LFC used as filler material, panels or blocks due to its low compressive strength. This research is believed to provide an optimal mix design for LFC that suitable for structural usage. The mechanical properties of LFC can be recognize and understand. Besides that, in this study, new types hybrid slab systems by using CFS sections and fully embedded into the concrete to replace the conventional reinforcement steel bar. The CFS skeletal, which were easy and fast erected by using bolts and nuts, with four different types of configurations were studied.

The lightweight slab system that involving using lightweight foamed concrete is predicted to have better flexural behaviour than the conventional slab system and in the meantime it reduces the selfweight of the slab system. Furthermore, this study may provide further additional information to the design guides in the current codes of practices.

1.6 Outline of thesis

The general information of the research subject including e.g. background information of the study, problem statements, objectives, scope of work and significant of the study are mentioned in Chapter 1. Chapter 2 consists of detailed background of the research and works done by previous researchers. The limitation from the previous research discusses in this chapter. Chapter 3 discusses on the analytical works involved in generating design formula and calculations for slab system. Experimental testing on trial mix design for lightweight foamed concrete discussed in Chapter 4. The obtained optimum mix design on its mechanical properties will also discussed in detail. Chapter 5 discusses about the full-scale experimental programme on slab flexural test that consists both normal weight slab system and lightweight slab system. The chapter contains the detail descriptions of the experimental investigations that carried out, material testing and also the critical review on the result discussion. Furthermore, the comparison made between both types of slab system and analytical study comprise in Chapter 5. The research works are summarized and concluded in Chapter 6, together with the recommendation for future works.

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