STRUCTURAL BEHAVIOUR OF CONCRETE FILLED COLD-FORMED STEEL CHANNEL WALL PANEL UNDER AXIAL LOADING

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ABSTRACT

The Government of Malaysia has promoted the usage of Industrial Building System (IBS) since the early 1960s. However, based on the IBS Roadmap 2003-2010 published by the Construction Industry Development Board Malaysia (CIDB), the factors contributing to the delay of IBS implementation in Malaysia are lack of knowledge among designers and requiring more local researches and developments, technologies and support services. One of the research areas is to develop a new type of load-bearing wall system to overcome the corrosion problem of reinforcement steel in the precast concrete wall panels. The aim of this study is to develop a new type of precast load-bearing wall panel system. The proposed system involved composite cold-formed wall panel (CCFWP) which consists of concrete and cold-formed steel sections, where the steel sections act as reinforcements. The load carrying capacity and the buckling behaviour of individual wall studs, wall frames, and CCFWP were assessed and validated with the relevant code of practices, and data from previous studies. The empirical equation to estimate the load carrying capacity of CCFWP has been proposed. The structural behaviour of individual wall studs, wall frames and CCFWP were investigated using full-scale experiment. Influences of web and flange holes, wall frame arrangements, aspect ratio and slenderness ratio on load carrying capacity of individual wall studs, wall frames, and CCFWP were also studied. It was found that web and flange holes with 150 mm spacing provide adequate compressive strength for the wall studs, and Arrangement 1 with one middle stud is considered as the best arrangement of the wall frame since it yielded higher and consistent results. The increment in ultimate axial strength ratio for CCFWP is 4% when the slenderness ratio of the CCFWP increased from 6 to 13, and the increment in ultimate axial strength ratio is 7.3% when the aspect ratio increased from 1.67 to 3.33. From the validation process, the closest prediction of the ultimate axial load of CCFWP is provided by BS8110. Subsequently, the proposed empirical equation for CCFWP is modified from the empirical equation as in BS 8110 by incorporating the effect of slenderness ratio, aspect ratio, and the contribution of the cold-formed steel.

ABSTRAK

Kerajaan Malaysia telah menggalakkan penggunaan teknologi Sistem Binaan Berindustri (IBS) bermula pada awal tahun 1960-an. Walau bagaimanapun, berdasarkan IBS Roadmap 2003-2010 yang diterbitkan oleh Lembaga Pembangunan Industri Pembinaan Malaysia (CIDB), factor-faktor yang menyumbang untuk penangguhan pelaksanaan IBS di Malaysia adalah kurangnya pengetahuan di kalangan jurutera dan keperluan lebih banyak penyelidikan dan pembangunan, teknologi dan perkhidmatan sokongan. Salah satu bidang kajian adalah membangunkan sistem dinding galas beban yang baru bagi mengatasi masalah kakisan keluli tetulang dalam panel dinding konkrit pratuang. Tujuan kajian ini adalah untuk membangunkan sistem panel dinding galas beban yang baru. Sistem yang dicadangkan melibatkan panel dinding komposit keluli terbentuk sejuk (CCFWP) yang terdiri daripada konkrit dan keluli terbentuk sejuk yang bertindak sebagai tetulang. Kekuatan dan tingkah laku tiang dinding individu, bingkai dinding daripada keluli terbentuk sejuk dan CCFWP telah dikaji dan disahkan dengan kod amalan yang berkenaan, dan data daripada kajian terdahulu. Persamaan empirikal untuk menganggarkan kapasiti kekuatan menanggung beban bagi CCFWP telah dicadangkan. Ujian berskala penuh telah dilakukan untuk mengkaji kelakuan tiang dinding individu, bingkai dinding dan CCFWP. Pengaruh lubang pada web dan bebibir, susunan bingkai dinding, nisbah aspek dan nisbah ketinggian pada kekuatan tiang dinding individu, bingkai dinding dan CCFWP juga telah dikaji. Didapati bahawa lubang pada web dan bebibir tiang dinding individu dengan jarak 150 mm memberikan kekuatan mampatan yang mencukupi dan Susunan 1 yang mempunyai satu tiang dinding tengah adalah susunan bingkai dinding terbaik kerana ia memberi hasil yang lebih tinggi dan konsisten. Peningkatan nisbah kekuatan paksi muktamad untuk CCFWP adalah sebanyak 4% apabila nisbah ketinggian CCFWP meningkat dari 6 ke 13, dan peningkatan nisbah kekuatan paksi muktamad adalah sebanyak 7.3% apabila nisbah aspek meningkat dari 1.67 ke 3.33. Daripada proses pengesahan mendapati ramalan terhampir bagi kekuatan beban paksi muktamad CCFWP diberikan oleh BS8110. Seterusnya, persamaan empirikal yang dicadangkan telah diubah dari persamaan empirikal oleh BS8110 dengan mengambil kira kesan nisbah ketinggian, nisbah aspek dan sumbangan kekuatan keluli terbentuk sejuk.

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LIST OF ABBREVIATIONS

3-D	-	Three dimension
A1	-	Arrangement 1
A2	-	Arrangement 2
A3	-	Arrangement 3
A4	-	Arrangement 4
ACI	-	American Concrete Institute
AISI	-	American Iron and Steel Institute
AS	-	Australian standard
ASD	-	Allowable stress design
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
BS EN	-	British Standard Eurocode
BSI	-	British Standard Institute
CCFWP	-	Composite cold-formedwall panel
c/c	-	Centre to centre
CIDB	-	Construction Industry Development Board Malaysia
CSB	-	Calcium silicate board
DAT	-	Design Assisted by Testing
DSM	-	Direct strength method
EC	-	Eurocode
ECCS	-	European Convention for Constructional Steelwork
ELC	-	Enveloped laminar concrete
eqn	-	Equation
FB	-	Flexural buckling
FEA	-	Finite Element Analysis
FRP	-	Fiber reinforced plastic
GYP	-	Gypsum board
H1	-	Height 1-2920 mm or 2000 mm
H2	-	Height 2-1920 mm or 1500 mm
H3	-	Height 3-1420 mm or 1000 mm

H4	-	Height 4-920 mm
HS	-	High strength
IBS	-	Industrialized Building System
LB	-	Local buckling
LC	-	Lipped channel
LFC	-	Lightweight-foamed concrete
LRFD	-	Load and resistance factor design
LTB	-	Lateral torsional buckling
LVDT	-	Linear Voltage Displacement Transducer
Mh	-	Mid-height
Md	-	Middle
NS	-	Normal strength
OSB	-	Oriented strand board
P	-	Plain
PCSP	-	Precast sandwich panels
Qh	-	Quarter-height
OW	-	One way
R&D	-	Research and development
RC	-	Reinforced concrete
Sd	-	Side
SLS	-	Serviceability limit state
TC	-	Track channel
TW	-	Two way
U.S	-	United State of America
ULS	-	Ultimate limit state
WF	-	Wall frame
WFH	-	Web flanges holes
WH	-	Web holes
WOH	-	Without holes
WASTB	-	Computer program developed by Doh (2002)

LIST OF SYMBOLS

A_{eff}	-	Effective cross section area
A_c	-	Gross cross-sectional area
A_g	-	Area of gross cross-section
$A_{g,sh}$	-	Value of A_g for cross-section with sharp corners
A_s	-	Effective second moment area of the edge stiffener
A_{sv}	-	Area of vertical steel
A_{cp}	-	Cross section area of concrete in one pitch of wall
A_{net}	-	Net gross cross-section area
B or b	-	Width
b_p	-	National flat width or plane element
$b_{p,i}$	-	notional flat width of plane element i for a cross-section with sharp corners
b_{eff}	-	Effective width
c	-	lip
D	-	Overall thickness of wall
E	-	Young modulus of the section
e	-	Eccentricity of the load measured at right angles to plane of the wall
e_a	-	an additional eccentricity due to deflections in the wall panel $e_a = (H_{we})^2/(2500t_w)$
e_{tot}	-	$e_o + e_i$
e_o	-	First order eccentricity
e_i	-	Additional eccentricity including geometrical imperfections
f_{cu}	-	Concrete compressive strength
f_y	-	Tensile strength of the steel
f_{yb}	-	Basic yield strength
h	-	Height of wall panel
H	-	Effective height of wall panel
h_p	-	Overall depth of the cross section of polystyrene

$\frac{h}{t}$	-	Slenderness ratio (height/thickness)
$\frac{h}{L}$	-	Aspec ratio (height/length)
H_{we}	-	Effective height
I_s	-	Effective cross-sectional area of the edge stiffener
I_g	-	Second moment of area of the gross cross-section
$I_{g,sh}$	-	Value of I_g for a cross-section with sharp corners
I_w	-	Warping constant of the gross cross-section
$I_{w,sh}$	-	Value of I_w for a cross-section with sharp corners
k	-	0.8 for wall restrained against rotation at one or both ends
K	-	Spring stiffness per unit length
L	-	Length or width
L_{cr}	-	Buckling length
l_e	-	Effective height of braced wall
m	-	Number of plane elements
$N_{b,Rd}$	-	Design buckling resistance
N_u	-	Design axial strength of wall panel per unit length of wall (N/mm)
N_{Rd}	-	Axial resistance of rectangular cross-section
n	-	Number of curved elements
P_u	-	Ultimate axial compressive load of wall panel
$P_{u,L}$	-	Ultimate axial load of wall panel per unit length
P_{ue}	-	Experimental axial load capacity
P_{uc}	-	Calculation/theoretical/prediction axial load capacity
r_j	-	Internal radius of curved element j
t	-	Thickness of wall panel
t_{cor}	-	Steel core thickness
$\frac{t}{6}$	-	Eccentricity (wall panel thickness/6)
t_w	-	Thickness of wall panel
t_{red}	-	Reduced thickness
$\bar{\lambda}_d$	-	Relative slenderness of the stiffener
$\sigma_{cr,s}$	-	Elastic critical buckling stress

$\bar{\lambda}_{p,red}$	-	Reduced relative slenderness
χ_d	-	Reduction factor
$\bar{\lambda}$	-	Non-dimensional slenderness
χ	-	Reduction factor for the relevant buckling mode
γ_{M1}	-	Partial factor (resistance of member to buckling)
α	-	Imperfection factor
$\eta f_{cd.pl}$	-	Design effective compressive strength
ρ	-	Reduction factor for plate buckling ≤ 1.0
ρ_h	-	Amount of horizontal steel
ρ_v	-	Amount of vertical steel
ϕ	-	Strength reduction coefficient
$\emptyset$	-	Angle between two plane elements
α	-	Reduction factor to account for profiling of concrete
p	-	Pitch of profiles in wall
Φ	-	A value to determine the reduction factor

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CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia is known as one of the developing countries in the world with the number of population reaching 32 million in 2017 which is an increase of about 1.3% from 2016 (Bernama, 2017). As the population increases, the demand for facilities including housing areas for shelters, industrial areas for job opportunities and the urban areas also increases. With reverence to this issue, the function of the construction industry can take part in order to consummate these needs. In many countries, the construction industry plays an important role in the economic development. According to RAM Ratings (2016), the recorded growth in the construction of residential buildings at about 11% and the non-residential buildings recorded a 14% expansion from 2014. Therefore, the construction sector in Malaysia has proved to be the sector that ranked first in terms of its development economic in 2015.

Aligned with the growth of the construction industry and demand for housing in Malaysia, therefore the Construction Industry Development Board Malaysia also known as CIDB has initiated the use of the Industrialized Building System (IBS). IBS is a new construction technique that was introduced in Malaysia since the 1960s and the main objective is to solve the problem of shortage of houses. This is due to the available method of construction (conventional) is ineffective and incapable to deal with the incrementing demand of facility in Malaysia especially housing area and industrial area. According to CIDB, IBS can be defined as a construction activities that relate to the utilising of off-site prefabricated construction components and products such as beam, column, floor panel and wall panel. All the components will be transported, arranged and installed on-site (CIDB, 2003). The advantages of IBS construction technique is that it can reduce the on-site activities that lead to more organized construction site, thus significantly reducing the completion time of construction. Furthermore, the adoption of the IBS construction technique can reduce the use of unskilled workers, less volume of building material on-site, thus reducing wastage and increasing construction site cleanliness.

Based on Rahim and Qureshi (2018), the private sector in Malaysia is still cannot fully accept the use of IBS and CIDB is still in the process of encouraging the use of IBS in this sector. One of the factors that contributing to the delay of its implementation in Malaysia is insufficient knowledge on IBS method among designer (Kamarul et al, 2007). In order to overcome this problem, more local research and development (R&D), technologies and support services are required. One of the areas or components in IBS that can be developed is the load-bearing wall panels, where there is a need to produce an effective and suitable load-bearing wall panel system for IBS construction. Other than CIDB, the involvement of universities (academia), research institutes, contractors, consultants, and companies are critical towards the implementation of IBS.

Nowadays, the used of cold-formed steel in Malaysia construction sector is quite common but only familiar in the roof truss constructions. There are a few factors that limit the usage of cold-formed steel in Malaysia i.e. the market perception that the cold-formed steel is expensive and lack of knowledge among local design engineers and architects on the application and design of cold-formed steel structure. However, the application of cold-formed steel in a developed country is becoming very popular due to several advantages such as speedy construction, high strength to weight ratio, dimensional stability and recycle material (Billah et al, 2019). The application of the cold-formed steel sections is not limited to the interior non-load bearing and curtain walls, storage racks and various types of equipment but getting attention for use as load-bearing wall panel, floor panel and roof truss members in residential and commercial building (Hu, 2008).

The chapter onwards will discuss the new technology of a composite load-bearing wall panel with cold-formed steel section that has a great potential to be further studied and developed in Malaysian's IBS construction industry.

According to ACI 318-08 Clause 2.2, wall is defined as a vertical member used to enclose or separate spaces in a building or structure (Fanella, 2011). Walls as a structural element in the building system contribute to multiple different purposes and sometimes perform two or three roles together. Walls are divided into two types which is a non load-bearing wall and load-bearing wall. A non load-bearing walls usually has the function of dividing space, providing sound insulation and fire resistance requirements for the buildings. There are no others load carried by this wall, but only its own self-weight.

A load-bearing wall or sometimes called as structural walls whose length is not less than four times its thickness may perform the roles in two ways (Fisher, 1972). The first role, a load-bearing wall must be designed to resist the axial or vertical loads applied, in addition to their own self-weight. Second, the stabilising wall is also identified as shear walls are designed to resist the horizontal forces from wind load and earthquake load in the direction parallel to the length of the wall.

Walls can be classified as stocky wall if the effective height (l_e) divided by the thickness (h) of the wall does not exceed 15 and slender wall if $\frac{l_e}{h}$ greater than 15 (BS8110).

1.2 Statement of the Problem

Many low to medium rise buildings are built to have the load-bearing walls as the main supporting elements. The appropriate thickness of the load-bearing walls usually depend on the application and height of building. There is a possibility that an external wall could become unstable and failed if the applied load is greater than the strength of the material used, thus able to cause the collapse of the structure and building. Nowadays, the most popular materials used in the construction of load-bearing walls in buildings are concrete, blocks and bricks.

Traditionally, a brick wall was used as a load-bearing wall in low to medium-rise buildings, for internal walls and cladding of buildings but there are a few limitations when using a brick wall. Beasley (2000) mentioned that there are two broad categories of traditional wall failures which is the stability failures and serviceability failures. Stability failures include complete wall collapse or partial collapse and loose of pieces or crushing while stability failures include water leakage, formation of cracks or aesthetic deterioration to the structures. There are a few relevant factors in deciding the use brick walls from the construction point of view which are the obtainability of the skilled labour, the time of construction and the phasing of the overall building planning. This is because each brick must be mortared and placed by hand and as a form of 'wet' construction, the brick needs time to dry out and as a result slows down the rate of the construction. Other than that, bricks are susceptible to water absorption and when they absorb water they deteriorate quicker than other materials.

In the 20th century, most of the constructions started to change the direction of traditional brick walls to reinforced concrete walls. A few limitations and issues with brick walls were solved by using reinforced concrete walls. Nevertheless, reinforced concrete wall can fail due to inadequate strength thus end up to the mechanical failure, a reduction in durability and corrosion problem. When reinforcement bar corrodes, the oxidation products expand and results in the formation of cracks in the concrete, and finally unbonding the rebar from the concrete. The expansion of corrosion products will result in serious defects in reinforced concrete walls (Kyung et al, 2004).

Extensive studies also have shown that under high axial compressive load ratio, the conventional RC walls will have low ductility and limited deformation capacity when subjected to cyclic lateral loads (Qian et al, 2012).

Therefore, the precast concrete wall panel has been introduced as the newest product in the concrete industry and gaining popularity to replace the conventional brick walls and reinforced concrete walls. There are many advantages of precast concrete wall panels such as lightweight, speed of erection, fire resistance and minimum maintenance. However, the main problems encountered with the precast concrete wall panels is bulging of panels and heat transmission problem (Leabu, 1959). Popovic and Arnold (2000) also mentioned that due to the exposure to freeze-thaw cycles, the surface of precast concrete wall panels will develop cracks and shallow spalls, tend to caused corrosion to the embedded reinforcing steel.

The idea to use a cold-formed steel section as reinforcement in the wall instead of reinforcement bars can overcome the corrosion problem in the precast concrete wall panels. Rondal (2000) and Davies (2000) reported that the production of economic coated steel coils and improving the technology of manufacture for cold-formed steel have given a solution to the architectural and corrosion problems in construction and resulting to the increased use of cold-formed in new structural applications. It is believed that, application of a cold-formed steel can derive benefits to the new composite cold-formed load-bearing wall panel proposed in this study due to its characteristics of high strength to weight ratio and high resistance to corrosion. Therefore, the main intentions of this research are to fulfill the demands for more innovative wall panel construction method and to overcome the shortcomings in the conventional wall construction and problems in precast concrete wall panels.

1.3 Objectives of the Study

The aim of this study is to develop a new load-bearing wall panel using concrete and cold-formed channel section. In order to achieve this aim, several objectives are identified as follow:

1. To assess the load carrying capacity and buckling behaviour of individual wall studs and cold-formed wall frames proposed in this study.

2. To validate the performance of the individual wall studs and cold-formed wall frames by comparing the experimental results and predictions by Eurocode 3.

3. To investigate the structural behaviour of the proposed composite cold-formed load-bearing wall panel (CCFWP) by means of the experimental investigation of full-scale tests.

4. To propose an empirical equation to estimate the load carrying capacity of the proposed CCFWP.

1.4 Scope of the Study

The focus of this study is to develop a new type of load-bearing wall panel utilizing concrete and cold-formed channel section as a reinforcement in the wall panel. The scope of this study consists of two phases of experimental investigation. The first phase focuses on testing the cold-formed individual wall studs from lipped channel sections to determine the suitable position and spacing of drilled holes (shear connector) and testing of the wall frames with four different proposed arrangement. The proposed cold-formed wall frames are embedded in composite wall panels and act as the steel reinforcement. The second phase of experimental investigation focuses on testing the full-scale composite cold-formed wall panels (CCFWP) with different height of wall panels. The composite wall panels were prepared with normal strength concrete. All the specimens were tested under axial loading. The behaviour of CCFWP studies from the experimental results and observations are the load carrying capacity, load-deflection profiles, crack pattern, strain distribution, the efficiency of the wall frame arrangements and the influence of vertical steel.

The experimental results from the first and second phase of testing are validated by comparing with the predictions by Codes of Practices and previous researchers. A suitable empirical equation is proposed to determine the ultimate load carrying capacity of proposed CCFWP under axial compressive load.

1.5 Significance of the Study

Throughout this study, information about the structural behavior of the CCFWP is being provided. The results of this study are very important to provide further justification and important information on the CCFWP in terms of strength, failure mechanism, and deformation capacity under axial compressive loading. The information will assist in the design of CCFWP to be used as a precast wall panel and as an alternative to conventional reinforced concrete walls. An empirical equation proposed in this study is able to predict the ultimate load carrying capacity of CCFWP under axial compressive load. In addition, this study will broaden knowledge in the field of wall panels.

1.6 Thesis Outlines

This thesis consists of six (6) chapters. The outlines of each chapter are depicted as follows:

Chapter 1 - This chapter presents the background of the study, statement of the problem, objectives of the study, scope of the study and significance of the study.

Chapter 2 - This chapter presents the comprehensive review on the area of study including research on cold-formed steel wall frame, load-bearing composite wall panels, discussion on empirical equations developed from previous researchers and code of practices to predict the ultimate axial load of wall.

Chapter 3 - This chapter describes the methodology of the study. The fabrication of the individual wall studs, wall frames and CCFWP specimens. The detail description of the test set-up, instrumentation and procedure of the testing also presented.

Chapter 4 - This chapter presents and discusses the experimental results of individual studs test and wall frames test. The experimental results were verified using the current code of practice.

Chapter 5 - This chapter presents and discusses the experimental results of CCFWP test under axial loading. The theoretical validation of experimental results were performed by using empirical equations proposed by current code of practices and previous researchers. The suitable empirical equation also developed to predict the ultimate axial load capacity for CCFWP.

Chapter 6 - This chapter provides conclusions and recommendation for future works on CCFWP.

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