STRUCTURAL BEHAVIOUR OF COMPOSITE BEAMS WITH COLD FORMED STEEL SECTION

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To my beloved father, mother, wife and sons

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ABSTRACT

The use of composite beam in buildings has known to be more economical compared to bare steel beams with hot-rolled steel section, as the composite action between steel and concrete results in significant savings in steel weight and reduce the beam depth. However, the use of composite beam with cold-formed steel of lipped C-channel is yet to be established as the structural behavior of such beam is not well understood. This study presents and discusses the behavior of composite beam with cold formed steel section and innovative shear connectors. The composite beam comprises two cold formed steel of lipped C-sections oriented back to back to form I-steel beam and perpendicular metal decking concrete slab. Three types of bracket shear connectors namely single bracket (SBSC), double bracket (DBSC) and hot rolled plate (HPSC) shear connectors were developed and used; the proposed shear connectors were fixed to the web of steel beam by bolts. In addition, headed stud (HSSC) shear connector welded to the top flange of cold formed steel beam was also investigated. Push tests in accordance with Eurocode 4 were carried out to determine the strength capacity and ductility of the proposed shear connectors. Sequentially, full-scale beam tests were conducted to investigate the actual behavior of the composite beam with the proposed shear connectors. The length of full-scale specimen between supports is 4000 mm. Theoretical validation for the experimental results was performed based on the plastic analysis of composite beam. The experimental results of push tests showed very good strength with extreme deformation capacity for all bracket shear connectors suggesting that they are strong and ductile enough to provide composite action between steel beam and concrete slab. Also, it was observed that strength capacity of shear connector increases as the thickness of steel beam increases. For headed stud shear connectors, the stud possess strength capacity as high as its predicted strength. The results of full-scale beam tests showed very good agreement as compared to theoretical values that predicted based on push test results. The bending resistance and stiffness of the composite beams were improved up to 170% and 270% respectively as compared to non-composite cold formed steel beam. Composite beam with HSSC shear connectors showed the best performance as compared to composite beams with SBSC, DBSC and HPSC shear connectors. Also, the results showed that the bending resistance of the composite beam increases as the thickness of steel beam increases. It is concluded that the proposed composite beams with cold formed steel section are strong enough to be used in small and medium size buildings.

ABSTRAK

Penggunaan rasuk rencam dalam bangunan telah diketahui lebih menjimatkan berbanding dengan rasuk keluli dengan keratan keluli tergelek panas, kerana tindakan komposit antara keluli dan konkrit dapat menghasilkan penjimatan berat keluli yang ketara dan mengurangkan kedalaman rasuk. Walau bagaimanapun, penggunaan rasuk komposit dengan keluli terbentuk sejuk daripada *C-channel* berbibir belum lagi terlaksana kerana kelakuan struktur rasuk tersebut tidak difahami dengan baik. Kajian ini membentangkan dan membincangkan kelakuan rasuk komposit dengan keratan keluli terbentuk sejuk dengan penyambung ricih inovatif. Rasuk komposit terdiri daripada dua keratan keluli terbentuk sejuk daripada *C-channel* berbibir bertemu belakang bagi membentuk rasuk I dan papak konkrit dengan dek logam yang serenjang. Tiga jenis penyambung ricih iaitu kurungan tunggal (*SBSC*), kurungan berganda (*DBSC*) dan plat gelek panas (*HPSC*) telah dibangunkan dan digunakan; penyambung ricih yang dicadangkan telah dipasangkan kepada web rasuk keluli menggunakan bolt. Di samping itu, penyambung ricih *headed stud* (*HSSC*) yang dikimpal kepada bebibir atas rasuk keluli terbentuk sejuk juga disiasat. Ujian tolakan berdasarkan *Eurocode 4* telah dijalankan untuk menentukan keupayaan kekuatan dan kemuluran bagi penyambung ricih yang dicadangkan. Ujian rasuk berskala penuh dengan panjang spesimen 4000 mm telah dijalankan untuk menyiasat kelakuan sebenar rasuk komposit dengan penyambung ricih yang dicadangkan. Pengesahan secari teori bagi keputusan eksperimen telah dijalankan berdasarkan analisis plastik rasuk rencam. Keputusan ujian tolakan yang menghasilkan kekuatan yang sangat baik dengan keupayaan ubah bentuk yang melampau bagi semua penyambung ricih kurungan menunjukkan bahawa mereka cukup kuat dan cukup mulur untuk menyediakan tindakan rencam antara rasuk keluli dan papak konkrit.Selain itu, dapat juga diperhatikan bahawa keupayaan kekuatan penyambung ricih meningkat apabila ketebalan rasuk keluli meningkat. Untuk penyambung ricih *headed stud, stud* tersebut mempunyai kapasiti kekuatan setinggi kekuatan yang diramalkan melalui kiraan berdasarkan *Eurocode 4*. Keputusan ujian berskala penuh menunjukkan keputusan yang sangat baik berbanding dengan nilai teori yang diramalkan berdasarkan keputusan ujian tolakan. Rintangan lenturan dan ketegaran rasuk rencam juga telah meningkat sehingga 170% dan 270% berbanding dengan rasuk bukan rencam tergelek sejuk. Kesimpulannya, rasuk rencam yang dicadangkan dengan keratan keluli terbentuk sejuk adalah cukup kuat untuk digunakan dalam bangunan bersaiz kecil dan sederhana.
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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Numerical coefficient (0.5 for beams)
A_{cc}	-	Shear area of concrete per connector
A_{eff}	-	The effective area
$A_{g,sh}$	-	Gross cross-sectional area with sharp corners;
A_g	-	Gross cross-sectional area;
A_s	-	Tensile stress area of the bolt
A_{tr}	-	Total area of transverse reinforcement
b	-	Slab thickness
b_0	-	Average rib width
b_f	-	Steel section flange width
$b_{p,i}$	-	Notional flat width of plane element i for a cross-section with sharp corner;
d	-	Diameter of stud or bolt
e_1	-	The end distance from the centre of the bolt to the adjacent end of the connected part in the direction of load transfer (refer to EN199313)
E_{cm}	-	Modulus of concrete
$F_{V,Rd}$	-	Shear resistance of bolt
$F_{b,Rd}$	-	Bearing resistance of bolt
$F_{n,Rd}$	-	Net-section resistance of connected part
f_{bv}	-	Shear buckling strength
f_u	-	The smallest ultimate tensile strength of the connected parts
f_{ub}	-	Ultimate tensile strength of the bolt
f_{yb}	-	Basic yield strength
f_{yr}	-	Yield strength of reinforcement
f_{ck}	-	Cylinder compressive strength at test date

f_u	-	Specified ultimate tensile strength of the material of the stud but not greater than 500 N/mm2
h_p	-	Height of rib
h_{sc}	-	Height of connector
h_w	-	Web height between the midlines of the flanges
k_i	-	Reduction factor
P_{Rd}	-	Design shear resistance of stud
λ_{LT}	-	Non-dimensional slenderness
γ_{M1}	-	Partial factor taken as 1.0
γ_{m0}	-	Partial factor
L_c	-	Contact length between the concrete and the flange of the steel section
m	-	Number of plane element;
M_{Ed}	-	The total bending moment at the section
$M_{b,Rd}$	-	Design buckling resistance moment
$M_{c,Rd}$	-	Design moment resistance
M_{cr}	-	is the elastic critical moment fpr lateral – torsional buckling
$M_{f,Rd}$	-	The design plastic moment of the composite section ignoring the web
$M_{pl,Rd}$	-	The design plastic moment of the fully composite section irrespective the class of the web
M_u	-	Ultimate bending moment
n	-	Number of curved element;
N	-	Number of shear connector
n_r	-	Number of studs per rib
P_{pre}	-	Strength capacity of shear connector
P_u	-	Ultimate load
Q_{rib}	-	Strength of shear connector in a rib
Q_{sol}	-	Strength of shear connector in a solid slab
q_u	-	Shear capacity per perfobond rib connector
$R_{w,Rd}$	-	Resistance of web crippling
r_j	-	The internal radius of curved element j.

s_s	-	Nominal length of stiff bearing, taken as the distance over which the applied load is effectively distributed at a slope of 1:1
t	-	Thickness of the thinner connected part
t_{sc}	-	Thickness of shear connector
V_{Ed}	-	The total vertical shear at the section
$V_{b,Rd}$	-	Design shear resistance
$V_{bw,Rd}$	-	Shear resistance of the section
W_{eff}	-	Effective section modulus
α_{LT}	-	is an imperfection factor
γ_{M2}	-	Partial factor recommended to be taken as 1.25
χ_{LT}	-	Reduction factor of lateral torsional buckling
ϕ_j	-	Angle between two plane element;
ɣ	-	Partials factor
α	-	Dimensional coefficient
δ	-	Deflection of beam
δ_u	-	Ultimate slip of shear connector
δ_{uk}	-	Characteristic slip capacity of shear connector
w	-	Average rib width
δ	-	Factor considering the rounded corners effects;
ρ	-	The reduction factor for plate buckling
ϕ	-	Slope of the web relative to the flanges

ABBREVIATIONS:

AISI	-	American Institute of Steel and Iron
BS5950	-	British standard for design of steel structures
CIDB	-	Construction Industry Development Board, Malaysia
Eurocode 3	-	European standard for design of steel structures
Eurocode 4	-	European standard for design of composite structures
SBSC	-	Single Bracket Shear Connector
DBSC	-	Double Bracket Shear Connector
HPSC	-	Hot rolled Plate Shear Connector
HSSC	-	Headed Stud Shear Connector

FSSBSC	-	Full-Scale composite beam with Single Bracket Shear Connector
FSDBSC	-	Full-Scale composite beam with Double Bracket Shear Connector
FSHPSC	-	Full-Scale composite beam with Hot rolled Plate Shear Connector
FSHSSC	-	Full-Scale composite beam with Headed Stud Shear Connector
IBS	-	Industrialised Building System
LVDT	-	Linear Variable Displacement Transducer

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The population growth in the world requires an increase in the demand of residential and housing construction. Dannemann, (1982) introduces low cost house construction system using cold formed steel sections. The later are one of the most efficient and economic structural members (Bryan, 1980). In the past 20 years, extensive growth of using cold formed steel sections in residential construction has been reported. Pekoz (1999) states that, in the United States, there were about 500 homes built in light gauge steel in 1992. This number rose to 15,000 in 1993, 75,000 in 1994. In Australia, about 40,000 new houses using load bearing cold formed steel framing are constructed per year (Hancock and Murray, 1996). In Malaysia, recent development in IBS includes the increased usage of light steel trusses consisting of cost-effective profiled cold-formed channels and steel portal frame systems as alternatives to the heavier traditional hot-rolled sections (CIDB, 2003). With fast and accurate manufacturing, ease handling and transportation, high strength-to-weight ratio, efficiency in cost and material, speedy in erection, fully recyclable, and durability, cold-formed steel sections could be an alternative economic structural components and frame systems for residential and commercial construction (Dannemann, 1982; Yu, 2000; Allen, 2006). The increase in the use of cold-formed steel as construction materials leads to an increase in the research done in this area (Ghersi, et al., 2002). There are three primary areas of cold formed steel applications; namely, framing, metal buildings, and racks (Schafer, 2011).

Cold-formed steel members are steel products that made from sheets or coils by cold rolling, press brake or bending brake method (Yu, 2000). The thickness of cold formed steel members can go up to 8 mm (EN1993-1-3, 2006). However, the available thickness in Malaysian market is ranged from1 mm to 3 mm. In 1930s, the development in cold formed steel construction faced difficulties due to lack of design specification (Yu, et al., 1996). Thus, extensive research was conducted at the end of 1930s and first American Institute of Steel and Iron (AISI) specification was published in 1946 as end product of this research (Haws, 1996). Subsequent improvements and developments led to enhance and modernize the AISI specifications. Later, new standard specifications in UK, Canada, China, Japan, India and other countries were published.

Recent developments in the technology of producing cold formed steel sections includes ultra-high yield stress, possibility of welding, more complex section shapes, enhancement of corrosion resistance and controlled rolling and forming technology encouraged the builders, contractors and companies to use cold formed steel sections as primary framing system in low-rise and midrise construction and as secondary framing system in high-rise or long-span construction (Davies, 2000; Ziemian, 2010).

The main governed instability characteristic of cold formed steel members comes from its thinness that induces the local, lateral, flexural, distortional buckling before reach its yielding point. Thus, extensive researches and investigations have been conducted (Lau and Hancock 1987; LaBoube 1993; Rogers and Hancock 1997; Wang and Li 1999; Wilkinson and Hancock 2000; El-Kassas, Mackie et al. 2002; Schafer 2002; Holesapple and LaBoube 2003; Stephens and LaBoube 2003; Yu and Schafer 2003; Young 2004; Young and Ellobody 2005; Guzelbey, Cevik et al. 2006; Yu and Schafer 2006; LaBoube and Findlay 2007; Dubina 2008; Pala 2008; Ranawaka and Mahendran 2009; Kumar and Kalyanaraman 2012; Macdonald and Heiyantuduwa 2012) to study the stability problems and improve the behaviour of cold formed steel members. The current codes of practice cover the design considerations for plain cold formed steel members subjected to compression, tension, bending, shear or combinations. However, the use of cold formed steel members in composite with concrete is still very limited. This is due to the fact that, no standard specifications have been made for cold formed steel section as composite members.

This study investigated the structural behaviour of composite beam with cold formed steel section. Innovative new shear connectors suitable for cold formed steel section are proposed to perform the composite action between steel beam and concrete slab. In addition, the feasibility of using welded stud shear connectors with cold formed steel beam is investigated. The findings from this study may lead to expanding of the use of cold formed steel sections in Malaysian construction industry and promoting the use of the proposed shear connectors and composite beams as alternative construction materials for possible construction implementation. Also, it may improve the understanding about the feasibility of using the welded stud as a shear connector for composite beam with cold formed steel section.

1.2 Problem Statement

Recently, cold formed steel members are extensively used in construction industry. Builders, contractors and companies have realized the efficiency of using cold formed steel sections as primary framing system in low-rise and mid-rise construction; and as secondary framing system in high-rise or long-span construction (Allen, 2006; Ziemian, 2010).

However, the efficiency of using such structural members with concrete to form composite beam members is not properly investigated. Exploitation of composite principles seems appropriate for promoting the use of cold formed steel sections to a wider range of applications (Irwan, et al., 2008). For example, composite beam with cold-formed steel section could be an alternative economic beam for reinforced concrete and hot rolled steel beams in medium and small size buildings (Hossien, 2005). Also, in cold formed steel housing and residential buildings, designing beams as composite beams rather than the current practice where the beams designed as non-composite beams could improve their strength capacity and stiffness, and in some cases provide simple fabrication and installation without the requirements of specially trained labor (Fox, et al., 2008). However, the thinness of cold formed steel section materials is a big challenge faces the designers and researchers. Introducing composite action between cold formed steel beam and concrete slab should be based on their strength and ductility requirements. New shear connectors should also be proposed so that the cold-formed steel section can develop composite action with the slab system.

1.3 Objectives of Study

The main objective of this study is to study the structural behaviour of cold formed steel concrete beam with the proposed shear connectors. The purpose of the newly invented shear connectors in this study is to develop a composite beam system that has better capacities and performance as compared to non-composite beam.

Four specific objectives are considered in this study:

1. To evaluate the mode of failures, strength capacities and ductility of the proposed shear connectors,
2. To study the structural behaviour of composite beam with cold formed steel section and the proposed shear connectors,
3. To examine and study the feasibility of using welded stud shear connector with cold formed steel beam,
4. To validate the performance of the proposed composite beam by comparing the theoretical predictions and experimental results.

1.4 Scope of Study

The scope of this study consists of an experimental program. The experimental program is designed to provide a better understanding of the structural behaviour of the proposed composite beams. Innovative new shear connectors suitable for composite cold formed steel beam are introduced. They are namely; single bracket shear connector (SBSC), double bracket shear connector (DBSC) and hot rolled plate shear connector (HPSC). In addition, headed stud shear connector (HSSC) welded to the top flange of steel beam is investigated. This is to study the feasibility of using welded studs with cold formed steel sections. Proposed equations are adopted to predict the strength capacity of proposed shear connectors depending on their mechanism to resist the longitudinal load. The experimental program comprises of two phases. In the first phase, push tests are carried out in accordance with Eurocode 4. Based on load-slip curves that obtained from the push tests, the strength capacities and ductility of proposed shear connectors are determined. The second phase is designed to investigate the structural behaviour of the proposed composite beams. The proposed composite beam comprises two cold formed lipped steel C-sections oriented back-to-back to form an I-steel beam, and profiled concrete slab. Full-scale simply supported beam specimens of 4000 mm length between supports are tested using four-point load system. The beam is subjected to two point loads with 1025 mm far from the supports. This system of loading produces a constant region of pure bending moment between the point loads. Hence, the ultimate flexural capacity of the proposed composite beam is determined. Later, the results from full-scale tests are used to verify the theoretical results. Theoretical analysis using current design methods of composite beam is conducted based on push test results. A comparison between theoretical values and experimental results is conducted to validate the use of current design methods of composite beam for designing the proposed composite cold formed steel concrete beams.

The details of the works involved are divided into several tasks according to their subsequent, where organized into relevant chapters as described in section 1.6.

1.5 Significance of Research

Composite beams are extensively used in construction industry due to their efficiency in strength, stiffness and saving materials (Nie, et al., 2006; Tahir, et al., 2009). To date, headed stud shear connectors are commonly used to perform the composite action between steel beam and concrete slab (Lawson, et al., 2001). However, it was found that headed stud shear connectors create a significant tripping hazard on working surfaces at site (US Department of Labor, 2001). Thus, alternative new shear connectors need to be developed. Also, in small and medium size buildings where the span is very short (about 4000 mm), the use of composite beam with hot rolled steel beam is not effective due to the loss of interaction between steel beam and concrete slab (Johnson,1981). The proposed composite beams in this study could be an alternative to be suitable in place of composite hot rolled steel concrete and reinforced concrete beams in small and medium size buildings.

Also, in light-weight residential and commercial buildings, cold formed steel members are used as floor beams and joists, and designed as non-composite beams (Popo-Ola, et al., 2000; Grubb, et al., 2001; Ghersi, et al., 2002). Such beams need to be checked for buckling and twisting and most likely they fail due to lateral-torsional buckling prior to the attainment of their full capacities (Ziemian, 2010). Big steel sections are then used resulting in space and material consuming. Thus, the validation of using cold formed steel sections with concrete as a composite beam could significantly increase their strength and stiffness capacities. The concrete slab could provide lateral bracing that prevents the cold formed steel section to fail under lateral-torsional buckling. Also, it could improve the resistance of top flange and reduce its tendency to buckle under compression.

1.6 Structures of Thesis

In this section, the organization of thesis is presented according to each following chapter

Chapter 1 provides background of the topic, problem statement, and objectives of study, scope or research and significance of the study.

Chapter 2 presents a comprehensive review on the area of study and all published works related to the current study.

Chapter 3 provides detailed description on the methodology of this study. The fabrication of new shear connectors and their configurations are presented. Push test specimen configuration, fabrication, instrumentation and test procedure are described. Also, detailed description on the full-scale beam test i.e. fabrication of the specimen, rig setup and procedure are outlined.

Chapter 4 presents and discusses the experimental results of materials properties and push test. Tensile test results of steel materials are presented. Load-slip curves of all push test specimens and their strength capacity and ductility as well as failure modes are discussed.

Chapter 5 contains the discussion on the experimental results of full-scale beam tests. Load-deflection curves of all specimens and their failure modes are discussed. The theoretical validation of experimental results is done using current practice design method. A comparison between experimental and theoretical results is conducted.

Chapter 6 provides conclusions, recommendations and future work development.

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