STRUCTURAL BEHAVIOUR OF HIGH-STRENGTH CONCRETE COLUMN CONFINED WITH STEEL STRAPPING TENSIONING TECHNIQUE SUBJECTED TO CONSTANT AXIAL AND LATERAL CYCLIC LOADS

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To my family and friends

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ABSTRACT

Ductility is the main consideration in designing reinforced concrete (RC) structures. The application of high-strength concrete (HSC) in columns is able to reduce the column sizes and optimize the floor area of a building. Besides, reduction in building self-weight can minimise the seismic load acting on the building. Established Steel Strapping Tensioning Technique (SSTT) by previous researchers was chosen in this study due to its low material cost and ability to enhance the ductility of HSC. This research is conducted to study the effectiveness of SSTT in improving the ductility and deformability of HSC columns subjected to constant axial load and reversed cyclic horizontal loading which represents simulated seismic excitation since SSTT is yet to be tested under cyclic loading. A series of experimental work consisted of ten specimens with concrete compressive strength of 35 MPa, 55 MPa and 85 MPa were carried out. The first series of five specimens with 55 MPa were tested with different spacing of steel strapping confinement. Second group of specimens with 85 MPa were confined with different steel strapping layers and longitudinal reinforcement ratio of 1.78%, 3.56% and 5.12%. The behaviours of concrete columns were presented in hysteresis load-ductility graphs to determine the performance of confined HSC columns. The ductility and deformability of each columns were compared with the pre-analysed estimations. Results showed that with the increase of steel strapping as confinement, the ductility and shear resistance of HSC column improves significantly according to certain configurations. Ultimate displacement of the 85 MPa specimen was improved from 37.82 mm to 71.52 mm due to SSTT confinement. HSC column is able to achieve the same level of ductility as normal strength concrete column by reducing the spacing of SSTT confinement. The structure behaviours of SSTT-confined HSC columns under simulated seismic load have been examined and SSTT will benefit the construction industry as an alternative solution in confining HSC.

ABSTRAK

Kemuluran struktur konkrit bertetulang (RC) merupakan perkara utama yang dipertimbangkan dalam merekabentuk struktur RC. Aplikasi konkrit berkekuatan tinggi (HSC) pada tiang boleh mengurangkan saiz tiang dan meningkatkan penggunaan luas lantai dalam banggunan. Dengan itu, kesan daripada daya gempa bumi dapat dikurangkan pada bangunan tersebut. Teknik pra-tegangan jalur besi (SSTT) yang telah diperkenalkan oleh penyelidik terdahulu dipilih untuk kajian ini kerana kos bahan yang rendah dan keupayaannya meningkatkan kemuluran HSC. Penyelidikan ini dijalankan untuk menilai keberkesanan SSTT dalam meningkatkan kemuluran dan kebolehcanggaan HSC yang tertakluk kepada beban paksi berterusan dan kitaran beban mendatar yang mewakili simulasi gempa bumi kerana SSTT belum pernah diuji dengan beban kitaran. Beberapa siri percubaan yang melibatkan sepuluh spesimen merangkumi konkrit dengan kekuatan mampatan 35 MPa, 55 MPa dan 85 MPa telah dilakukan. Siri pertama yang terdiri daripada lima spesimen 55 MPa telah diuji dengan jarak kurungan jalur besi yang berbeza. Kumpulan kedua dengan kekuatan 85 MPa telah dikurungi dengan lapisan jalur besi yang berbeza dan nisbah tetulang pada 1.78%, 3.56% dan 5.12%. Sifat-sifat tiang konkrit dipersembahkan dalam graf beban-kemuluran untuk menentukan prestasi tiang HSC yang telah dikurung. Kemuluran dan kebolehcanggaan yang diuji pada setiap tiang dibandingkan dengan anggaran pra-dianalisis. Keputusan menunjukkan penambahan jalur besi sebagai kurungan meningkatkan kemuluran dan rintangan ricih tiang HSC juga meningkat secara ketara dengan konfigurasi yang tertentu. Anjakan muktamad spesimen 85 MPa telah ditingkatkan daripada 37.82 mm kepada 71.52 mm kesan daripada kurungan SSTT. Tiang HSC juga dapat mencapai tahap kemuluran yang setaraf dengan tiang konkrit berkekuatan biasa dengan mengurangkan jarak tutupan SSTT. Sifat - sifat struktur HSC yang terkurung dengan SSTT telah diperiksa dengan simulasi beban gempa dan SSTT akan memberi manfaat kepada industri pembinaan sebagai penyelesaian alternatif untuk mengurung HSC.

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A_e	-	80 % of cross section area (mm^2)
A_g	-	gross section area
A_v	-	effective area in the direction of applied shear
b_w	-	web width
C	-	depth of neutral axis from compression zone, (mm) centroid
d	-	effective depth of column section
D	-	overall section depth, (mm)
D'	-	diameter of section confined between shear links
f'_{cc}	-	confined compressive stress
f_y	-	yield strength of the main reinforcement
f_{yh}	-	yield strength of shear reinforcement, (MPa)
f'_c	-	specified compressive strength of concrete
k	-	flexural ductility influence factor (refer to Table 2.3)
L_p	-	plastic hinge length
M/VD	-	shear aspect ratio
$MF(f'_c)$	-	concrete strength factor
$MF(n)$	-	axial load factor
$MF(\rho)$	-	longitudinal bars factor
P	-	factored axial load, (N)
s	-	spacing of shear reinforcement
u	-	ductility
V_a	-	nominal shear strength provided by axial load, (N)
V_c	-	nominal shear strength provided by the concrete
V_d	-	shear demand
V_n	-	nominal shear strength
V_s	-	nominal shear strength provided by shear reinforcement

x	-	depth of compression zone at critical section, (mm)
Δ_u	-	ultimate displacement
Δ_y	-	member yield displacement
ε'_{cu}	-	ultimate confined concrete strain
ε_{cu}	-	concrete strain
ε_{sc}	-	strain of steel under compression
ε_{st}	-	strain of steel under tension
ε_y	-	steel strain (0.002) determine from tensile test
Φ_u	-	ultimate curvature
u_Φ	-	curvature ductility
u_Δ	-	displacement ductility
θ	-	angel of principle shear crack to column axis
σ_{sc}	-	compressive stress in longitudinal reinforcement
σ_{st}	-	tensile stress in longitudinal reinforcement

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CHAPTER 1

INTRODUCTION

1.1 Background

The earthquake happened at Ranau, Sabah at 07:15 a.m. on 5th June 2015 created a shock to our nation. The seismic event lasted for 30 seconds and was measured a magnitude of 6.0 on Richter's Scale. It was the strongest earthquake in Malaysia since 1976 (MetMalaysia, 2015). The aftershocks were continuous until 27th July 2015 ranging in the magnitude from 1.6 to 6.0. The aftershocks have mainly taken place at Tuaran, Kota Belud, Penampang, Papar and Tambunan (MetMalaysia, 2015).

Sabah lies within the Sunda Plate and is experiencing uplift of about 0.5 mm each year towards the north-west. The movement was believed to initiate the earthquakes in the onshore area. The impact of the last earthquake resulted in loss of lives where eighteen people with five different nationalities died. Besides, the affected buildings and infrastructures had been severely damaged and were closed for rehabilitation and repairs (The Star, 2015). Consequently, millions of ringgits have been spent for the rectification works.

In response to the incident, National Security Council was ordered to introduce an early warning system for earthquakes for important building such as school buildings. Besides, seismic centre was also introduced in Sabah (The Star, 2015). Unfortunately, earthquake is unpredictable by the current technology, unlike other natural events such as eclipse which could be predicted accurately (Chakrabarti *et al.*, 2008). Therefore, having buildings that can sustain seismic is the safer bet. However, the existing buildings in the region are not adequate for seismic resistance. Hence, upgrading of current buildings are urgently needed to protect the structure from failure as well as giving an ample of time for residents to evacuate safely.

1.2 Problem Statement

Buildings in seismic region demand large inelastic displacements. Numerous research works have been conducted to determine the behaviour of concrete columns under seismic loading in the past decades. Existing external confinement method such as concrete jacketing, steel jacketing and fibre reinforced polymer (FRP) was found effective in improving the ductility of columns. However, these methods are costly and labour intensive (Chakrabarti *et al.*, 2008). This makes confining all buildings in earthquake-prone regions extremely costly.

The usage of high strength concrete (HSC) can reduce the self-weight and optimise floor area. Reduction of self-weight could minimize the impact of seismic loading on the buildings. However, the brittle behaviour of HSC has been a major concern. Thus, improving the material's ductility is a balancing deed. Regulating brittleness of HSC is critical to provide safe and sound structure prior to vacant possession and operation of the building.

A recently established low-cost external confinement method that is steel strap tensioning technique (SSTT) was found to be effective in improving the ductility of column. Besides, SSTT material is light-weight. However, information on the effectiveness of active confining method using steel strap tensioning technique (SSTT) under seismic loading is still very limited. Hence, a more focused experimental work is needed for the development of comprehensive database towards safe and sound design of confined HSC column.

1.3 Aims and Objectives

The aim of this study is to investigate the structural behaviour of SSTT-confined HSC columns under simulated seismic loading. The detail objectives of the study are decided as follows:

i. To determine the deformability of reinforced concrete (RC) columns under cyclic loads using SSTT as a confining method;

ii. To evaluate the effectiveness of SSTT in improving the ductility of RC columns;

iii. To investigate the applicability of current design methods on estimating the ductility of SSTT-confined HSC columns;

Generally, this research presents the experimental work to determine the behaviour of SSTT-confined HSC columns subjected to the combination of constant axial load and cyclic lateral load. The performance of confined columns in terms of ductility, failure mode, and deformation are investigated.

1.4 Significant of study

This study clarifies the effects of different variables, such as concrete compressive strength, longitudinal reinforcement ratio and transverse confining configurations on HSC columns subjected to cyclic loading. Besides, this research gives better understanding on the behaviour of HSC columns confined by SSTT which has yet to be explored in seismic condition. Additionally, the outcomes of data analysis will enrich the existing database. Proven and physically tested results are significant for future research in establishing design guidelines.

1.5 Scope of study

The aim and objectives of this research can be achieved within the following scope of work:

i. Review of related previous experimental works to determine suitable test setup.

ii. Design and construction of specimens with concrete compression strength of 35 MPa, 55 MPa and 85 MPa which represent normal strength concrete and high strength concrete respectively.

iii. Design and construction of specimens with main reinforcement content of 1.7 %, 3.5 % and 5 %. The contents are decided based on minimum number of longitudinal at 1.7 % which are four numbers of 10 mm diameter high tensile steel. Meanwhile, 3.5 % and 5 % were used to represent medium and high longitudinal bar ratio, p_L.

iv. SSTT confinement at different spacing from 25 mm, 50 mm, and 75 mm were adopted. The spacing was selected based on suitable workability. Unconfined specimen also was prepared as control specimen.

v. The effects of confining layers were investigated. The number of confining layers tested were one, two and three layers to represent for low confining level to high confining levels respectively.

1.6 Outline of Thesis

The following chapters are described in this thesis to present the findings and outcome of this research.

Chapter 1 explains the significant of this research with background of the study. The cost involves in achieving higher level of ductility is believe to be solve by the application of SSTT which are light-weight and low-cost. The objectives and the scope of study are stated clearly to ensure the success of this study.

Chapter 2 presents the literature review of confined HSC and methods of confinement. Active and passive type of confinement were briefly discuss to have better understanding on confinement technology. In addition, the well-established SSTT technique was introduced in this chapter. Related seismic test on RC columns were studied to define suitable testing variables and their respective range. Theoretical consideration on shear, flexure and deformation capacity were also deliberated. Failure modes of RC columns were also reviewed.

Chapter 3 explains the method on construction of the specimen, test setup and the test procedure. Specimens detail and parameters selection were also described. Preliminary testing of materials for specimen were reported prior to the construction of specimen. The yield displacement were established under force-controlled loading before the loading continues under displacement-controlled.

Chapter 4 reports the result of the experimental test with visual observation of the column behaviour throughout the testing up to failure. Results were analysed to determine the response to the columns under quasi – static reversed cyclic loading. Ductility of the specimens was analysed and compared with the predicted ductility using graphical and residual limit method.

Chapter 5 concludes the findings of this research. The objectives and the overall aims of the research were discussed. Lastly, few recommendations are propose for future work to obtain more input into design and theoretical consideration.

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