BEHAVIOUR OF EXTERNALLY-CONFINED HIGH-STRENGTH CONCRETE COLUMN UNDER UNIAXIAL CYCLIC COMPRESSION

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To my beloved mother and father

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ABSTRACT

The behaviour of confined high-strength concrete under uniaxial cyclic compression is of vital important for the study either for seismic retrofitting technique of concrete columns or for the structure designs in seismic regions. Hence, the effectiveness of external wrapping with steel straps in reducing the brittleness and enhancing the strength and ductility of HSC column under uniaxial cyclic compression are to be properly understood. Twenty four high-strength concrete columns with diameter of 150 mm and 300 mm in height were cast, wrapped with pre-tensioned steel strap at spacing of 15 mm and tested to failure under both uniaxial monotonic and uniaxial cyclic compression load test. Test results obtained from steel strap-confined high-strength concrete cylinders are presented and examined, which allows a number of significant conclusions to be drawn, including the existence of an envelope curve, dependency of plastic strain to the number of layers of confinement, the cumulative effect of loading cycles, mode of failure under external confinement, etc. The present results are also compared with several results from previous study for various types of confined-concrete. The present study indicates that the column pre-tensioned with steel straps, performed better than the unconfined high-strength concrete columns. It is proved that externally confinement using steel straps do help to control the brittleness and at the same time, enhancing the ductility up to 56.2% and compressive strength up to 108.5% . The envelope curve of uniaxial cyclic loading almost coincides with the corresponding monotonic loading test, with a dependent plastic strain to the amount of layers of confinement.

ABSTRAK

Kelakuan konkrit berkekuatan tinggi terkurung di bawah beban mampatan paksi *cyclic* adalah sangat penting untuk kajian sama ada untuk baik pulih tiang konkrit atau reka bentuk struktur di kawasan yang mengalami gempa bumi. Oleh itu, keberkesanan kurungan dengan lilitan keluli dalam mengurangkan kerapuhan dan meningkatkan kekuatan dan kemuluran tiang konkrit berkekuatan tinggi di bawah beban mampatan paksi *cyclic* hendaklah dibuat kajian. Dua puluh empat tiang konkrit berkekuatan tinggi berdiameter 150 mm dan berketinggian 300 mm disediakan, dipra-tegangkan dengan lilitan keluli pada jarak 15 mm dan diujikaji dengan beban mampatan paksi *monotonic* dan beban mampatan paksi *cyclic* sehingga tiang mengalami kegagalan. Kajian tingkah laku tiang konkrit berkekuatan tinggi ini dinilai dengan menggunakan lengkung liputan, perhubungan terikan plastik dengan bilangan lapisan lilitan keluli kurungan, kesan kumulatif beban mampatan *cyclic*, mod kegagalan dan lain-lain lagi. Keputusan kajian ini juga dibandingkan dengan beberapa keputusan kajian lepas. Kajian ini menunjukkan tiang ditegangkan dengan lilitan keluli mempunyai prestasi yang lebih baik berbanding dengan tiang konkrit berkekuatan tinggi yang tidak ditegang dengan jalur keluli. Kajian ini membuktikan bahawa tiang ditegangkan dengan lilitan keluli mampu mengawal kerapuhan konkrit dan pada masa yang sama, meningkatkan kemuluran sehingga 56.2% dan kekuatan mampatan sehingga 108,5%. Di samping itu, lengkung liputan bagi beban mampatan paksi *cyclic* berlaku pada lengkung yang dengan graf tegasan-terikan bagi beban mampatan paksi *monotonic*. Kajian ini juga membuktikan bahawa nilai terikan plastik bergantung kepada bilangan lapisan lilitan kurungan keluli.

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A'_c - Area of concrete section

A_c - Area of core of section enclosed by the perimeter spiral or hoop

A_{cc} - Effective area of confined concrete enclosed by perimeter spiral or hoop

A_s - Area of steel section

A_e - Area of effectively confined concrete core

b_c - Core dimensions to centerlines of perimeter hoop in x direction

d_s - Diameter of spiral between bar centers

d_c - Core dimensions to centerlines of perimeter hoop in y direction

d'' - Nominal diameter of lateral ties in inches

d - Nominal diameter of longitudinal steel bars in inches

E_c - Tangent modulus of elasticity of concrete

E_{sec} - Secant modulus of confined concrete at peak stress

E_u - Tangent modulus at the beginning of the unloading branch

E_{re} - Tangent modulus at the returning point

$\varepsilon_{\mathrm{un}}$ - Axial unloading strain

ε_c - Longitudinal compressive strain of concrete

ε_{cc} - Strain at maximum concrete stress f'_{cc} of confined concrete

ε_{co} - Strain at maximum concrete stress f'_{co} of unconfined concrete

ε_{sp} - Spalling strain

ε_{pl} - Irrecoverable or inelastic strain

ε_{ro} - Coordinate of the strain of reloading located in an unloading branch or in a cracked state

ε_{85} - The strains at 85% of the peak compression strength after the full peak compression strength

ε_{50} - The strains at 50% of the peak compression strength after the full

peak compression strength
f_c' - Cylinder compressive strength of concrete
f_y - Yield strength of steel
f''_y - Yielding stress of the lateral steel
f'_{cc} - Compressive strength of confined concrete
f'_{co} - Unconfined concrete strength
f'_l - Effective lateral confining pressure from transverse reinforcement
f_{un} - Reversal (unloading) compressive concrete stress
f_{ro} - Coordinate of the load of reloading located in an unloading branch or in a cracked state
f_{c0} - The peak compression strength in the unconfined specimens
f_{cc} - The peak compression strength in the confined specimens
h'' - Length of one side of the rectangular ties in inches
k_e - Confinement effectiveness coefficient
n - Number of longitudinal steel bars
P_{cr} - Load at first visible cracking
P'_{max} - Maximum axial load
ρ_{cc} - Ration of area of longitudinal reinforcement to area of core of section
ρ'' - Volumetric ratio of lateral reinforcement
ρ - Volumetric ratio of longitudinal reinforcement
s' - Clear vertical spacing between spiral or hoop bars
s - The center-to-center spacing of the lateral ties in inches
w_i' - The i^{th} clear distance between adjacent longitudinal bars

CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, wide application in high-strength concrete have been found in construction industry due to the lower unit weight for a given strength with potential seismic advantages, reduced member dimension and reinforcing requirement, and more economical construction (Weston T. Hester, 1980). However, there is a major problem with high-strength concrete. Although high-strength concrete exhibit high compressive strength, high-strength concrete generally more brittle and less ductile than normal strength concrete. It is important to make sure that the minimum level of ductility is provided during designing the high-strength concrete (Neville A. M., 2002).

In Malaysia, most of the concrete structures are not designed using earthquake specification. Although Malaysia is free from earthquake intrusion, there still have some collateral impact when earthquake happened on neighbouring country. The earthquake impact will cause severe damages to the structures due to inadequate confinement of concrete, leading to shear anchorage and splice failures of concrete members. It is expensive and almost impossible to demolish and rebuilt the existing vulnerable structures, therefore innovative rehabilitation and strengthening techniques are needed to ensure the life expectancy of many existing building can be extended (Hasan M. et. al., 2008).

This report presents the results of an experimental study on the behaviour of externally confined high-strength concrete using steel strap under uniaxial cyclic compression. Twenty four high-strength concrete column specimens with different layers of steel strap wrapping are tested in order to investigate the external lateral confinement effect on the strength and ductility properties of high-strength concrete under uniaxial cyclic compression load. The effect of external confinement was performed by pre-tensioning steel straps in discontinuous rings with proposed width and thickness around the column specimens. Test results obtained are assessed and presented in this report.

1.2 Problem statement

Although there are many successful applications and researches conducted on high-strength concrete over the years, there is still a lack of confidence in the use of high-strength concrete among the code drafting committees, civil engineering, consultants, designers and clients in most countries. The main key points for the limited usage of high-strength concrete are its high brittleness and low ductility which are the primary emphasis in the assessment of safety (Mazen, S. Z., 2005). Many of the researches conducted only emphasized on short-term based and laboratory mix only. However, when deal with the long term based and commercial mix, issues concerned with the properties, such as strength and ductility will arise.

In the past decade, many studies have examined the monotonic stress-strain behaviour of unconfined and confined concrete (Hasan M. et. al., 2008, Saadtamanesh H. et. al., 1994, Weena P. L., et. al., 2005, and Yong Y. K., et al., 1988). Besides, extensive researches have been conducted on the stress-strain behaviour of unconfined and confined concrete under cyclic compression (Cheong H. K. and Perry S. H., 1993 and Lam L. et al., 2006), there were limited studies concerned of confined high-strength concrete under cyclic compression (Weena, P. L., et al., 2004). There exist many uncertainties in several issues concerning the high-strength concrete, including the validity of envelope curve for the concrete, the effect of loading history on the stress-strain response, and ultimate condition of confined concrete using steel strap under uniaxial cyclic compression in comparison with those of uniaxial monotonic compression.

Therefore, the study of high-strength concrete column confined with the steel-straps subjected to uniaxial cyclic compression load is very important and will enhance the knowledge on the composite material. It can be applied to retrofit the existing building in potential seismic region and at the same time, to increase the confidence in the use of the high-strength concrete.

1.3 Research significance

This report presents the test results of a study on the externally-confined high-strength concrete columns with steel strap subjected to uniaxial cyclic compression load. The study also investigated on the effect of confinement using steel straps on the compressive strength and ductility of the externally-confined high-strength concrete column in fundamental simulation of earthquake loading (i.e. uniaxial cyclic compression load). At the same time, the effect of confinement ratio to the externally-confined high-strength concrete column will also be investigated.

1.4 Scope of study

This study focused on the stress-strain relationship, compressive strength and ductility of the externally-confined high-strength concrete column under uniaxial cyclic compression load. The interested parameters to be investigated are confinement ratio (volumetric ratio of steel strap), method of testing for hardened concrete (uniaxial monotonic compression load and uniaxial cyclic compression load), compressive strength and ductility of the high-strength concrete specimens. Due to time constraint, only the column specimens with designed compressive strength of 60 MPa will be cast and investigated in this study.

1.5 Objectives

The objectives of this study are as follows:

i) To study the stress-strain relationship of externally-confined high-strength concrete column specimen under uniaxial cyclic compression load.

ii) To study the dependency of deformation of externally-confined high-strength concrete column specimen to the volumetric ratio.

iii) To compare the test results between present and previous studies.

CHAPTER 6

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