STRESS-STRAIN BEHAVIOUR OF HIGH-STRENGTH CONCRETE WITH LATERAL PRE-TENSIONING CONFINEMENT

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BY ABDULLAH ZAWAWI BIN AWANG

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ABSTRACT

High-strength concrete is currently being used in columns of multi-storey building all over the world. Although, it offers superior properties, it is relatively a brittle material. This study intends to improve the ductility of the concrete using a pre-tensioning lateral confinement technique. It investigates the effects of the technique on strength and ductility of the concrete and develops model equations to predict the stress-strain behaviour of confined concrete. The basis of the technique is to apply a pre-tensioning force to relatively low cost steel straps wrapped around the cylindrical concrete specimens. The experimental work was carried out using cylindrical specimens with a dimension of 100mm in diameter and 200mm in height and concrete compressive strength were fixed at 50, 60 and 80 MPa. The parameters studied including different properties of steel straps, various spacing between straps, number of layers of straps and different levels of pre-tensioning stress in the steel straps. The confined specimens were tested in compression until failure under monotonic and cyclic loading conditions. Data collected from the test included mode of failure, loads at peak and ultimate condition, and longitudinal and lateral strains in both concrete and straps. The data were analysed based on volumetric ratio of confinement which is a function of strength of steel straps, compressive strength of concrete, spacing and number of layers of straps. The experimental results show that the pre-tensioning technique using steel straps enhanced the ductility as well as strength of the concrete as the volumetric ratio increases. The results also depicted the ability of the technique to improve the ductility and strength of the concrete, especially for concrete with higher compressive strength by effectively utilising the confinement material. Moreover, the layers of straps had also delayed the onset of volumetric expansion and, undoubtedly, the concrete failure. Based on the analysis, new equations of strength and strain enhancement with confinement coefficients of 2.62 and 11.6 respectively, using pre-tensioning technique had been developed to predict the stress-strain behaviour of confined high-strength concrete.

ABSTRAK

Konkrit kekuatan tinggi banyak digunakan terutamanya dalam pembinaan tiang bangunan tinggi di serata dunia. Walaupun konkrit ini mempunyai sifat-sifat yang baik, tetapi ia secara relatif merupakan bahan yang rapuh. Projek penyelidikan ini bertujuan untuk meningkatkan kemuluran konkrit berkekuatan tinggi menggunakan teknik kurungan sisi pra-tegangan. Ia melibatkan kajian kesan penggunaan teknik ini keatas kekuatan dan kemuluran konkrit dan pembangunan persamaan matematik bagi menganggar hubungan tegasan-terikan konkrit kurungan sisi. Asas penting teknik ini adalah dengan mengenakan daya pra-tegangan pada jalur keluli yang dililit pada permukaan silinder konkrit. Ujian makmal telah dilakukan ke atas spesimen silinder konkrit berukuran 100 mm dia. x 200 mm tinggi, dan kekuatan mampatan konkrit ialah 50, 60 dan 80 MPa. Parameter kajian ini termasuk penggunaan jalur keluli yang berlainan sifat, perubahan jarak langkau antara jalur dan bilangan lapisan jalur dan juga tahap daya pra-tegangan yang dikenakan. Spesimen telah diuji di bawah beban mampatan statik dan juga beban kitaran sehingga gagal. Data yang diambil termasuklah mod kegagalan, beban pada ketika puncak dan muktamad, terikan tegak dan sisi bagi konkrit dan jalur keluli. Data telah dianalisis berdasarkan nisbah isipadu bahan kurungan, di mana ia mempunyai hubungkait dengan kekuatan keluli, kekuatan mampatan konkrit, jarak langkau dan bilangan lapisan jalur keluli. Keputusan ujian menunjukkan bahawa kemuluran dan juga kekuatan konkrit meningkat apabila nisbah isipadu bahan kurungan bertambah. Keputusan ujian juga menunjukkan teknik ini berupaya meningkatkan kemuluran dan kekuatan konkrit terutamanya bagi konkrit yang mempunyai kekuatan mampatan lebih tinggi melalui keberkesanan penggunaan bahan kurungan. Jalur keluli dalam berbilang lapisan juga didapati berupaya melewatkan pengembangan isipadu dan seterusnya kegagalan konkrit. Berpandukan kepada analisis, persamaan bagi kekuatan dan terikan konkrit masing-masing dengan pekali kurungan sisi 2.62 dan 11.6 telah dibangunkan untuk menganggar hubungan tegasan-terikan konkrit berkekuatan tinggi kurungan sisi menggunakan teknik pra-tegangan.

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LIST OF SYMBOLS

f_{cc}	-	Axial stress for confined concrete
f_{co}	-	Axial stress for unconfined concrete
f_{r}	-	Lateral confining stress
f_{ccl}	-	Maximum strength of confined concrete
f_{co}	-	Maximum strength of unconfined concrete
ε_{ccl}	-	Maximum axial strain of confined concrete
ε_{co}	-	Maximum axial strain of unconfined concrete
ε_{ccr}	-	Maximum lateral strain of confined concrete
ε_{cor}	-	Maximum lateral strain of unconfined concrete
ε_{c50cl}	-	Axial strain corresponding to 50% of peak stress at post peak region
ε_{c85cl}	-	Axial strain corresponding to 85% of peak stress at post peak region
ε_{v}	-	Volumetric strain
ε_{l}	-	Axial strain
ε_{r}	-	Lateral strain

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CHAPTER 1

INTRODUCTION

1.1 Background

High-strength concrete is an advanced construction material which offers superior properties such as higher strength, higher stiffness and better durability performance as compared to normal strength concrete. It can be produced using similar ordinary raw materials that are used in the production of normal strength concrete with a low water-cement ratio and special admixtures added. Nowadays, high-strength concrete is frequently used in columns of multi-storey building, in pre-cast concrete industries and in structures where strength and durability are emphasised in design consideration. It can reduce the cross-section area of the column and subsequently reduce the self-weight of the structure.

Generally, high-strength concrete can be produced by improving the density of the concrete mix so that it increases the strength of both the cement matrix and the interface between the matrix and the aggregates. However, an increase in the strength of the concrete results in increase in its brittleness or reduction in ductility. Concrete in brittle failure is not capable to resist any increase in load after reaching ultimate state. Then the load decreases very rapidly after peak and the type of failure is explosive. Whereas in ductile failure the load is remain constant at increasing deformation after peak stress. Therefore, in designing high strength reinforced concrete element, more precaution is required in term of ductility requirement especially for structural elements that are possibly exposed to lateral type of loading such as seismic, blast and wind loadings etc.

The lack of ductility of high-strength concrete can be seen as a steep ascending slope of a stress-strain curve followed by a very rapid post-peak descending branch of the curve as shown in Figure 1.1. In structural design point of view, this type of stress strain behaviour is not allowed and therefore the need to improve the ductility of the concrete is very crucial. One way of improving the ductility of concrete is by confining the concrete laterally. This method has been used for normal strength concrete since decades and it has been established that concrete confined laterally can increase the ductility and strength very significantly. The lateral confinement works if the concrete under axial compression produce sufficient lateral dilation. However, it is a fact that high-strength concrete exhibits smaller lateral expansion compared to normal strength concrete when subjected to axial or cyclic compression loads (Parenchio et al., 1978, Persson et al., 1973, Lee et al., 1988). Thus, this classical technique may be questioned and not be as effective when it is applied to high-strength concrete.

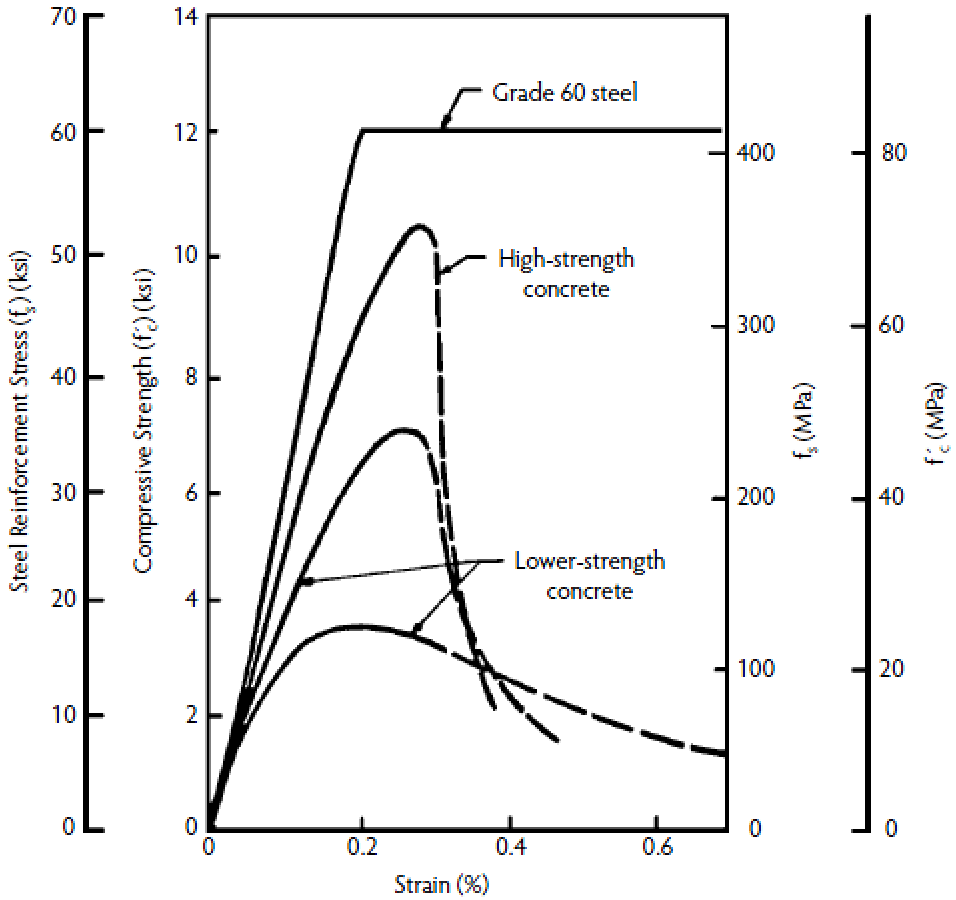

Figure 1.1 Concrete and steel stress strain relationship (ACI 363R)

This research was to investigate the effectiveness of lateral confinement using low cost steel straps with an innovative pre-tensioning and multilayer techniques to high strength concrete columns. The pre-tensioning stress applied to high-strength concrete column during installation may assist the column to mobilise the confinement material effectively and thus, enhanced the performance of the concrete in term of ductility and strength. A continuous steel straps in the form of multilayer distributed the confining stress exerted from concrete core during loading evenly between layers, thus extended the deformation of the column and subsequently delayed the failure.

1.2 Background of Concrete Confinement

Lateral confinement was originally introduced by Considere (Sakai and Sheikh 1989) in the form of internal spiral reinforcements in concrete columns. Richart, Brandtzaeg and Brown (cited from Roy and Sozen 1964) proposed the following relationship for strength and confining pressure of confined concrete, based on the results of extensive experimental programme from the first published research. This relationship is applied to both passive spirally reinforced and active hydraulically confined columns.

$$f_{cc} = f_{co} + 4.1 f_r \tag{1.1}$$

where:

f_{cc} is a longitudinal stress for confined concrete,
f_{co} is a longitudinal stress for unconfined concrete, and
f_r is a lateral confining stress.

Confinement reinforcement in a form of rectangular ties or spirals is commonly used to confine the concrete since the early years of reinforced concrete structural design. However, for high-strength concrete column, its high brittleness cannot be successfully eliminated using conventional ties and spirals (Krstulovic-

Opara and Thiedeman 2000); and the use of closely spaced interlocking ties or spiral to increase strength and ductility may associate with construction-related problems. For columns strengthening, there are three methods of confining the concrete, namely reinforced concrete jacketing, steel jacketing and fiber reinforced polymer (FRP) -wrapping. Reinforced concrete jacketing requires formwork and considerable increase in weight and cross-section of the column. Steel jacketing and FRP-wrapping are also labour intensive and costly. Although FRP confined concrete gains high strength enhancement, but evidences show that it fails in brittle mode (Ortega, 2006, Valdmanis et al. 2007). Furthermore, the jacket and wrapped confinement materials using the conventional techniques are proven not fully utilised especially for those concrete with small lateral dilation.

1.3 Significance of Research

The most fundamental issue in predicting the behaviour of reinforced concrete members is the stress-strain behaviour of the constituent materials. Concrete is used to resist compression and its behaviour in compression is important to the designer. If the behaviour of concrete subjected to uniaxial compression is known, the structural behaviour of reinforced concrete can be estimated.

The confinement steel requirements for normal-strength concrete are reasonably well established in current building codes (ACI 318, Canadian code, 1994) but not for the high-strength concrete; high-strength concrete real constitutive behaviour is almost nonexistent. This concern arise from the fact that the requirements for design and detailing of concrete in different model codes are primarily empirical and are developed based on experimental data obtained from testing the concrete specimens having compressive strength below 40MPa (ACI-363R, 1992). While designing a structure using high-strength concrete, the designer usually ignores the enhanced properties of confined concrete and possible changes in the overall response of the structure because of lack of adequate code guidance.

Also, the existing models for confined high-strength concrete are mostly derived by calibrating of experimental results of normal strength concrete. This may not be a safe approach since the mechanical properties of high-strength concrete differ with those of normal strength concrete.

This research provides experimental data on the stress-strain behaviour of confined and unconfined high-strength concrete. The data produced in this study were generated by considering variables such as different properties of steel straps, levels of pre-tensioning stress, numbers of layers and various amount of confinement. Such data are useful in order to develop a stress-strain model of high-strength concrete and compared with the existing models.

1.4 Objectives

The main objective of the research is to develop structurally ductile high-strength concrete with superior deformation property using a new technique of pre-tensioning and multilayer straps. The objective also includes generating of experimental data on an innovative confinement technique, with emphasis on investigating of the stress-strain response of confined concrete within elastic and inelastic ranges. The detailed objectives are as follows:

1. To develop a confinement technique using steel straps of various properties to provide lateral confining pressure on high-strength concrete.

2. To investigate the stress-strain behaviour of high-strength concrete confined with different levels of pre-tensioning force and varying number of strap layers.

3. To develop a model to predict the stress-strain behaviour of high-strength concrete with pre-tensioning lateral confinement technique.

1.5 Scope of Research

The objectives of the research programme were realised within the following scope:

- Review of previous research on the behaviour of concrete columns tested under different load conditions to determine relevant parameters for the present study.

- Review of existing stress-strain models for concrete confinement. The models are examined based on parameters used for their derivation such as concrete strength, type of confinement, type of confinement materials etc.

- Design and construction of stress and strain measurement devices for testing of high-strength concrete cylindrical specimens.

- Examination the suitable concrete mix designs and standards for high-strength concrete. Determination the proportions for concrete strength ranging from 50 to 80MPa.

- Investigation of the advantages and disadvantages of various properties of steel straps with the purpose of effective confining stress generating during wrapping and loading. The straps properties are vary in strength elongation and dimension as well.

- Examination of the various possibilities for connecting the straps and investigation of the effectiveness of the connection. Design suitable prefabricated straps in layers accounted for a self adjustment for purpose of distributing confining stress between layers.

- Evaluation interpretation and verification of test data with respect to specific parameters.

- Theoretical analysis of the behavior of confined concrete and compared with experimental results.

- Identification of a rational model for ductile high-strength concrete columns subjected to axial compressive loads.

- Preparation of thesis and presentation of results.

1.6 Outline of Thesis

In chapter 2, a literature survey on high-strength concrete and confinement is presented. How does confinement work and affects the ductility, the effect of configuration on confinement and the effective confinement area on different sections are discussed in different sections of this chapter. A review on conventional models of concrete confinement based on steel is also presented in this chapter.

Chapter 3 presents the experimental methodology. Four phases of the experimental programme are briefly described at the beginning of the chapter. Phases one and two focused on the effects of pre-tensioning stress to the confined concrete whereas phases three and four investigated on multi-layer effects to the concrete. All phases mentioned above investigated the behaviour of concrete in monotonic compression load. Some specimens were tested under cyclic load to verify the stress-strain response of the confined concrete. The prefabrication of innovative straps confinement is presented towards the end of the chapter.

Chapter 4 presents the fabrication and arrangement of new devices used to measure strain and deformation of confined concrete. The devices were calibrated using established confined normal strength concrete.

Chapter 5 presents all the results carried out in phases one and two. The stress-strain behaviour, volumetric strain and mode of failure for specimens confined in a single layer of different properties of steel straps are discussed. The results of unconfined specimen are also presented. The results presented in this chapter were emphasised on the effects of pre-tensioning stress and properties of steel straps.

Chapter 6 presents the stress-strain behaviour, volumetric strain and the failure mode for specimens confined in multilayer straps using different properties of steel straps. This chapter presents the results of experimental works in phases three and four. The concrete cylinder compressive strengths used in this project were 50, 60 and 80 MPa and the type of loads applied to the specimens were axial monotonic load as well axial cyclic load.

In Chapter 7, a detail discussion of the results is presented. The experimental data tabulated in chapters 5 and 6 were presented in form of graphs and verified with the data produced from existing models. Six equations are proposed to predict the stress-strain behavior of high-strength concrete. The results generated from the proposed equations were compared with existing stress-strain models available in literature.

In the final chapter, the general conclusions are drawn from the work described above and are presented together with recommendations for future research in this area.

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