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Constitutive Modeling of Confined High Strength Concrete

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ABSTRACT

The moment-curvature envelope describes the changes in the flexural capacity with deformation during a nonlinear analysis. Therefore, the moment-curvature analysis for reinforced concrete columns, indicating the available flexural strength and ductility, can be conducted providing the stress-strain relation for the concrete and steel are known. The moments and curvatures associated with increasing flexural deformations of the column may be computed for various column axial loads by incrementing the curvature and satisfying the requirements of strain compatibility and equilibrium of forces. Clearly it is important to have accurate information concerning the complete stress-strain curve of confined high-strength concrete in order to conduct reliable moment-curvature analysis to assess the ductility available from high-strength columns. However, it is not easy to explicitly characterize the mechanical behavior of confined high-strength concrete because of various parameter values, such as the confinement type of rectilinear ties, the compressive strength of concrete, the volumetric ratio and strength of rectangular ties, etc. So a stress-strain confinement model is developed which can simulate a complete inelastic moment-curvature relations of a high-strength reinforced concrete column

1. INTRODUCTION

High-strength concrete (HSC) is now readily available for various practical applications such as brides, offshore platforms, and buildings, as a result of ongoing progress in concrete technology. HSC offers many advantages, including excellent mechanical performance and ductility, which could result in initial and long-term cost reduction. HSC, however, is more brittle than conventional normal strength concrete (NSC).

Nonetheless, it has been shown that HSC columns can be having in a ductile manner under certain conditions. Hence, ACI-ASCE Committee 441 pointed out that columns subjected to axial-load less than 20% of column axial load capacity exhibited a good level of ductility when confined according to current ACI confinement requirements. The scientific community has not yet reached a consensus on required confinement reinforcement for ductile HSC columns. This can be

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limited number of tests on columns under cyclic flexure and significant axial compression, specifically with axial-load in the range of 20 to 50 % of column axial-load capacity. It has also been shown that the confinement mechanism was not described properly by exiting models. Therefore, in seismically active regions, structural engineers tend to avoid using HSC.

In the first part of this research, a stress-strain confinement model is developed which can simulate a complete inelastic moment-curvature relations of a high-strength reinforced concrete column. A confinement model, Analyzing the experimental data by multi-linear regression methods as SPSS[1)] program, this study proposes empirical equations to determine the peak stress and its corresponding strain of confined concrete expressed by tie stress, confinement effectiveness coefficient, the strength of concrete, the configuration of ties, and the rest variables. The second part of this research is to present analytical moment-curvature relationships for high-strength concrete columns.

2. ANALYTICAL MODELS

2.1 Effective confinement pressure for confined concrete

The determination of the strength and ductility of confined concrete is based on the computation of effective confinement pressure, which depends on the stress in the transverse reinforcement at maximum strength of confined concrete, and on the effectively confined concrete area. Where, it is difficult to exactly determine the tie stress. However the tie stress is related to the volumetric ratio of lateral ties, the confinement effectiveness coefficient, and other variables. Applying the multi-linear regression method with the experimental results, it is computed the stress in the transverse reinforcement at maximum strength of confined concrete as shown in Table1 (a).

2.2 Gains in strength, strain and ductility for confined concrete

The magnitude of the strength enhancement is a function of the volumetric ratio of lateral ties, the confinement effectiveness coefficient, and the stress in ties at maximum strength of confined concrete as important parameters to calculate the strength enhancement factor. Applying the multi-linear regression method, the strength enhancement is expressed by in Table1 (b).

The strain at peak stress and the strain corresponding to 85% of peak stress are dependent on

Table1 Parameters of Stress-Strain Relationship

$f_{hcc}=3.335(\frac{f_{yh}}{0.85f_{ck}})-21.74(\frac{100}{s'})-189.952(\rho_{s(\%)})-43.565(\rho_{s(\%)})+763.379(K_e)+$ $37.332(\rho_s f_{yh})-10.079(K_e \rho_s f_{yh})-229.313$	(a)
$K_s=7.129*10^{-6}(K_e \rho_{s(\%)} f_{hcc})+0.1386(K_e \rho_{s(\%)}\left(\frac{f_{hcc}}{0.85f_{ck}}\right)+1.106$	(b)
$\frac{\varepsilon_{cc}}{\varepsilon_{co}}=21.5\left[(K_s-1)\left(K_e \rho_s \frac{f_{hcc}}{0.85f_{ck}}\right)\right]+0.09912\left[(K_s-1)\left(\frac{f_{hcc}}{0.85f_{ck}}\right)\right]-0.0428(K_e \rho_s f_{hcc})+0$	(c)
$\frac{\varepsilon_{c85c}}{\varepsilon_{co}}=136.893\left[0.15K_s\left(K_e \rho_s \frac{f_{hcc}}{0.85f_{ck}}\right)\right]+0.187\left[0.15K_s\left(\frac{f_{hcc}}{0.85f_{ck}}\right)\right]-0.15(K_e \rho_s f_{hcc})+0.8$	(d)
$\varepsilon_{co}=\frac{4.26 f_{ck}}{\sqrt[4]{f_{ck}} E_c}$: *by Steunge* $\varepsilon_{c50c}=0.004+0.15(\frac{f_{le}}{f_{co}})$: *by Cusson* and *Paultre*	(e)

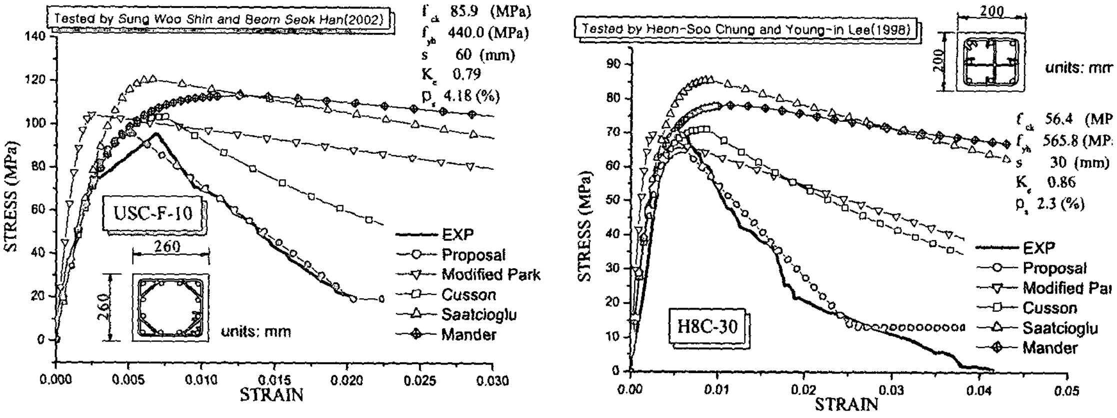

Fig 1 Comparison of stress-strain for HSC columns

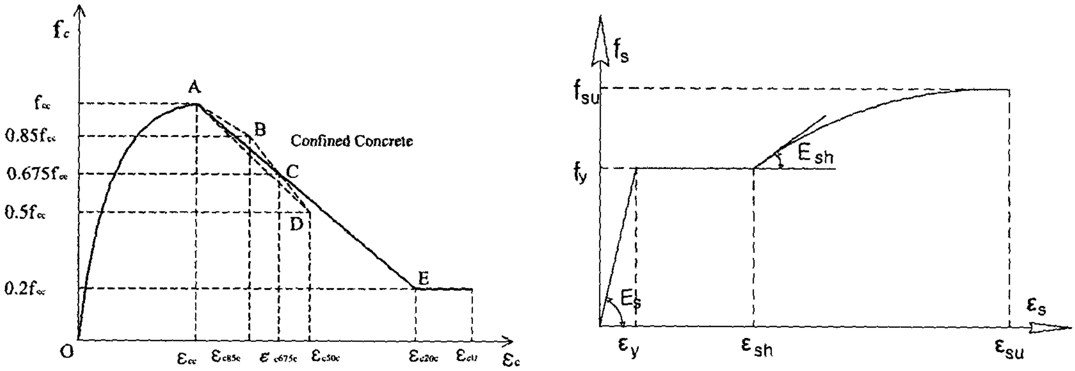

Fig 2 Analytical model for confined concrete and steel

the effectiveness of confinement. The following peak strain ratio is also computed by a regression method as shown in Table1(c),(d). Where, proposed by Cusson and Paultre[2], by the least absolute deviations method. The strain corresponding to 50% of peak stress can be calculated by Table1(e).

2.3 Stress-strain curves of confined concrete

Based on those relations, the stress-strain curve is established as (Fig. 2). Sample comparisons selected from different research programs, shown in (Fig. 1) the model yields good results for both the ascending and descending branches of the stress-strain curve.

2.4 Ultimate Concrete Compression Strain

In order to calculate the available ultimate rotation capacity at a plastic hinge in a reinforced concrete flexural member, it is necessary to be able to predict the ultimate concrete compressive strain ε_{cu} . The strain at peak stress does not represent the maximum useful strain for design purposes, as (Fig. 2). The useful limit occurs when transverse confining steel fractures, which

Table2 Application of Parameters of steel and concrete in tension

$f_s = f_{su} - (f_{su} - f_y)\left(\frac{\varepsilon_{su} - \varepsilon_s}{\varepsilon_{su} - \varepsilon_{sh}}\right)^P$		$P = E_{sh}\left(\frac{\varepsilon_{su} - \varepsilon_{sh}}{f_{su} - f_y}\right)$	(a)
$\sigma = f_{cr}[\exp[-(\varepsilon - \varepsilon_{cr}),$	$a = \left(G_f - \frac{1}{2} f_{cr}\, \varepsilon_{cr}\, l_{ch}\right) > 0$	$l_{ch} = \frac{E_{ci}\, G_f}{f^2_{ctm}}$	(b)
$f_{ctm} = f_{ctmo} \ln\left(1 + \frac{f_{cm}}{f_{cm}}\right.$	$G_f = G_{fo}\left(\frac{f_{cm}}{f_{cmo}}\right)^{0.7}$ for $f_{cm} \leq 80MP$	$G_f = 4.30\, G_{fo}$ for $f_{cm} \geq 80MP$	(c)
$0 \leq \varepsilon_1 \leq \varepsilon_{cr} \quad \sigma_1 = E_c\, \varepsilon_1$		$\varepsilon_1 > \varepsilon_{cr} \quad \sigma_1 = \frac{f_{cr}}{1 + \sqrt{500\, \varepsilon_1}}$	(d)

may be estimated by equating the strain-energy capacity of the transverse steel at fracture to the increase in energy absorbed by the concrete. Where, ε_{cu} was proposed by was proposed by T. Paulay and M.J.N. Priestly[3] is given by $\varepsilon_{cu} = 0.004 + 1.4\frac{\rho_s\, f_{yh}\, \varepsilon_{sm}}{f_{cc}}$.

2.5 Application model for reinforcing steel

The stress-strain relationship used for reinforcing steel in tension consists of three segments. The elastic and yield portions of the curve are linear and form a bilinear relationship. The strain-hardening portion is represented by a parabolic curve and follows the yield segment, as illustrated in (Fig. 2). Mander[4] found that the stress-strain curve in the strain hardening region ($\varepsilon_{sh} \leq \varepsilon_s \leq \varepsilon_{su}$)can be predicted by Table 2 (a).

2.6 Application model for concrete in tension

2.6.1 Tension stiffening in Plain concrete

Concrete can be considered as an elastic strain softening material in tension. The problem with this concept is the extent which the tension stiffening can be incorporated. Alternatively concrete can be assumed to be elastic-brittle in tension. When a crack occurs, the stress normal to it can be immediately released and drop to zero. The general strain softening model for concrete is given by Petersson[5] as shown in Table 2(b).

2.6.2 Tension stiffening in reinforced concrete

In order to predict accurately the post-cracking behavior of reinforced concrete elements, Collins[6] found that it was necessary to account for the average tensile stress which still exits in the concrete between cracks. To allow for this tension stiffening effect he specified a gradual unloading branch instead of an abrupt drop to zero stress level for the relationship of concrete as shown in Table 2(d).

2.7 Relations between tensile strength and compressive strength

Various relations have been proposed to estimate the axial tensile strength of concrete form its compressive strength. Table 2(c) is based on more recent data including also tests on high-strength concretes by the CEB-FIP MC. 90[7]

2.8 Fracture energy and characteristic length

The fracture mode of concrete subjected to tension allows the application of fracture mechanics concepts. The fracture energy is defined as the energy required propagating a tensile crack of unit area. As a rough approximation fracture energy may be estimated from the compressive strength of concrete tasking into account the maximum aggregate size as expressed by Table 2(c) from the CEB-FIP MC. 90[7)]

3. APPLICATION OF ANALYTICAL MODELS

A computer program was developed to carry out calculations for theoretical moment-curvature relations of the test specimens using the concrete stress-strain curves from the proposal model described previously. The required input data included cross-sectional dimensions of specimens, position, and amount of longitudinal steel including the location of laterally supported longitudinal bars, properties of longitudinal steel, the stress-strain of confined concrete, the stress-strain of unconfined concrete, and applied axial load.

The fiber section analysis is a numerically intensive method for determining the cross strength and stiffness of member cross sections. In the fiber model, the cross section is discredited into many small regions where the constitutive relationships are based on stress-strain model and each region represents a fiber of material running longitudinally along the member. Each fiber can be assigned one of several constitutive models representing either reinforcing steel, or concrete with

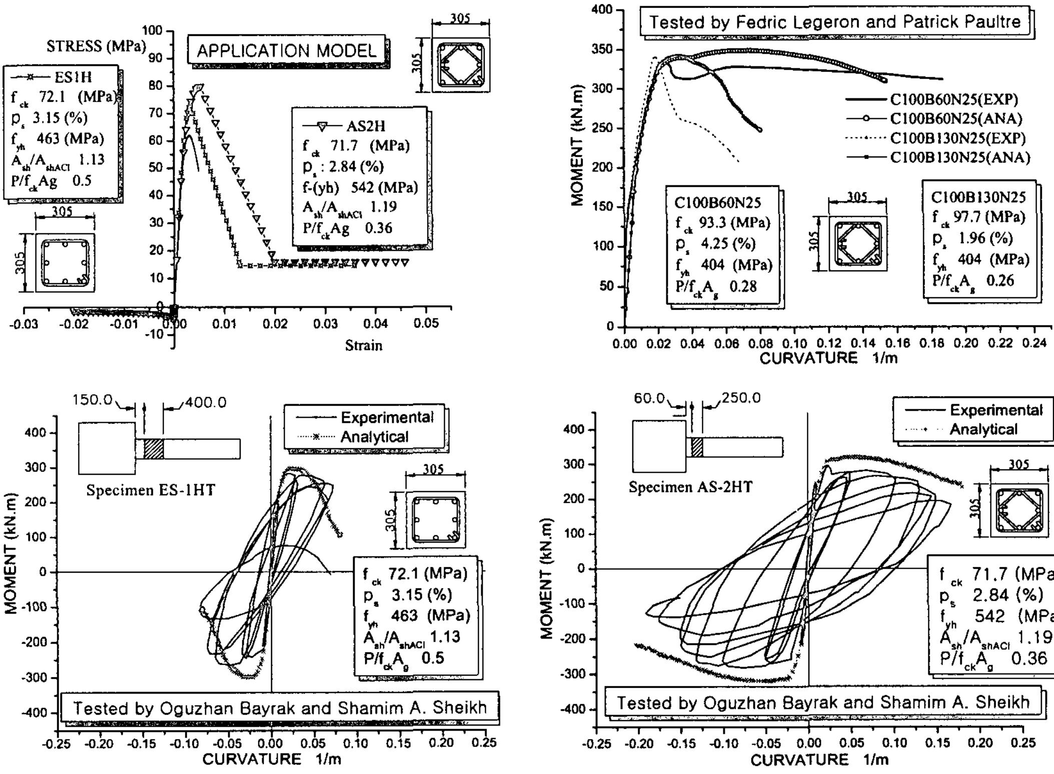

Fig 2 Comparison of Moment-Curvature Curves

varying amounts of confinement. The method assumes plane sections to remain plane, thus implying full compatibility between the confined concrete and unconfined concrete components of cross section

4. SUMMARY AND CONCLUSION

The strength and flexural ductility of HSC columns have been investigated using a fiber element model incorporating nonlinear constitutive models accurate for high-strength concrete. The accuracy of the analysis has been substantiated comparisons to tests of HSC columns subjected to axial forces and HSC columns subjected to axial compressive and cycle lateral loads. On the basis of the analytical and experimental studies, the following conclusions were drawn.

1) This model is applicable to high-strength concrete, covering a strength range between 40 and 90 MPa. The developed HSC model is shown to superior to other models in predicting test results of the compressive stress-strain curves of the confined high-strength concrete under concentric load.
2) A series of models for predicting the behavior of confined high-strength concrete columns is proposed as part of a potential improved design process. The series of detailed models predicted moment-curvature of cantilevers confined high-strength concrete columns reasonably well.

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