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Modelling Cyclic Stress-Strain Behavior of Confined Concrete

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Abstract: Present trend in composite construction is towards the use of concrete-filled steel tubular structures in bridge piers and high-rise buildings. Such structures exploit the best attributes of both steel and concrete, thus allowing the engineer to maintain manageable member sizes while obtaining increased stiffness, strength and ductility particularly essential for earthquake resistance. In light of the severe structural damage caused by recent earthquakes, such as the 1994 Northridge earthquake, the 1995 Kobe Earthquake and the 1999 Taiwan Earthquake, studies are presently being conducted on the performance of various types of filled steel composite members in an attempt to supplement efforts geared towards evolving earthquake resistant structures. In this paper the results of a research program aimed at studying the cyclic stress-strain response of concrete confined by steel tubes is presented. A confinement model for concrete confined by steel tubes has been developed and adopted in the Finite Element Analysis of concrete-filled steel tubular columns under cyclic loading. The stress-strain curve of confined concrete was determined based on the compatibility in the lateral expansion between concrete and the steel tube. The results of the predictions from the proposed confinement model shows good agreement with the experimental results of concrete filled columns. The comparisons indicated that the proposed model has the potential to be used for predicting the cyclic stress-strain curve of core concrete confined by steel tubes with sufficient accuracy

1 Introduction

Present trend in composite construction is towards the use of concrete-filled steel tubular structures in bridge piers and high-rise buildings. Such structures exploit the best attributes of both steel and concrete, thus allowing the engineer to maintain manageable member sizes while obtaining increased stiffness, strength and ductility, particularly essential for earthquake resistance. In light of the severe structural damage caused by recent earthquakes such as the 1994 Northridge earthquake, the 1995 Kobe Earthquake and the 1999 Taiwan Earthquake, studies are presently being conducted on the performance of various types of filled steel composite members in an attempt to supplement efforts geared towards evolving earthquake resistant structures.

Concrete-filled steel tubes (CFT) are used as beam-columns in buildings and piers in bridge construction especially in earthquake prone regions due to their high ductility, strength and energy absorption capacity. In concrete-filled tubes, steel resists tension forces and confines the core concrete, and the concrete prevents or delays the local buckling of the tube and resists the compressive load. These mutual effects increase the ductility and stiffness of the column. Also, the stiffness and strength degradation of CFT is not as severe as that of hollow tube or reinforced concrete.

Numerical techniques provide valuable information to understand the inelastic cyclic behavior of concrete-filled tubes if the accurate definition of the material is provided. There are well defined steel material models in the literature, such as the modified two surface model (Mamaghani et al. 1995, Chen et al. 1995). However, available concrete models have simple cyclic behavior which does not represent the smooth concrete behavior. On the other hand, Cheng and Mander (1994) proposed cyclic behavior for confined and unconfined concrete. This model has been used in the analysis of reinforced concrete structures. In order to use this model in the analysis of concrete-filled tubes, post-peak control parameters and confined concrete strength are proposed.

2 Confinement Action in Concrete-Filled Tubes

In-filled concrete prevents or delays the local instability of the thin-walled tube, and the tube creates a triaxial stress state in the core concrete, so concrete shows better post-peak behavior and strength

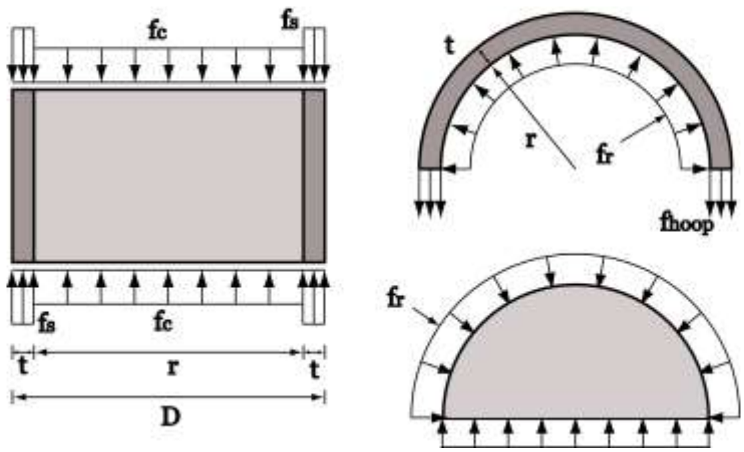

Figure 1: Stresses on concrete and steel in circular CFTs

capacity. This mutual effect is explained by concrete steel interaction: the initial Poisson's ratio of the concrete (0.15-0.25) is less than steel (0.28-0.30) (Gardner and Jacobson 1967). As the load increases the lateral expansion of the unconfined concrete becomes greater than the steel tube due to crack formation inside the concrete and radial pressure develop between the concrete and steel around the peak stress. At this stage, the concrete stressed triaxially and the steel tube biaxially. Figure 1 shows the stresses on the concrete and steel for circular concrete-filled tubes (Gardner and Jacobson 1967). The shape of the tube, length-to-depth ratio of the column, and the end conditions play an important role in the behavior of the column.

3 Definition of Parameters

In circular concrete-filled tubes, steel is under biaxial stress, so longitudinal stress and hoop stress are depend on each other. Due to this interdependency, it is difficult to propose parameters from the test results. For that reason, parameters are adopted or proposed from the available concrete models. Confined concrete strength of the available models, Sakino and Sun (1994) and Susantha (2001), are compared with each other. Comparison showed that the Sakino and Sun model predicts the confined concrete strength better than the Susantha model. Confined strength is the function of material properties and geometric dimensions of the section and is given by

$$f'_{cc} = \gamma_u f'_c + 4.1 f_r \tag{1}$$

where, f'_{cc} is the confined strength of concrete, f'_c is the characteristic strength of concrete, γ_u is the shape factor and f_r is the lateral pressure applied by the steel tube on the concrete. The shape factor is given by Eq. 2 and lateral pressure is given by Eq. 3.

$$\gamma_u = 1.67 D^{-0.112} \quad (D \text{ in mm}) \tag{2}$$

$$f_r = -0.19 \frac{2t}{D-2t} f_y \tag{3}$$

where, *D* is the diameter of the tube, and *t* is the thickness of the tube.

As seen in Eq. 4, the post-peak control parameter, *r*, is proposed by using the Sakino and Sun model. The r values are calculated from the Sakino and Sun model by iteration from different fictitious test data. Then, mathematical expression is proposed by the curve fitting method. If the ratio of confined strength to effective characteristic concrete strength, which is the characteristic strength multiplied by shape factor, is greater than 1.5, it is expected that good confinement is provided by the tube This ratio is called K.

$$r = -0.0152 Ln\left(\frac{D}{t}\frac{f'^{5}_{cc}}{f_y\sqrt{\varepsilon'_{cc}}}\right) + 0.6647 \qquad \text{For K > 1.5} \tag{4}$$

Figure 2 shows the best fit curve to the *r* values which were calculated using the Sakino and Sun (1994) concrete model.

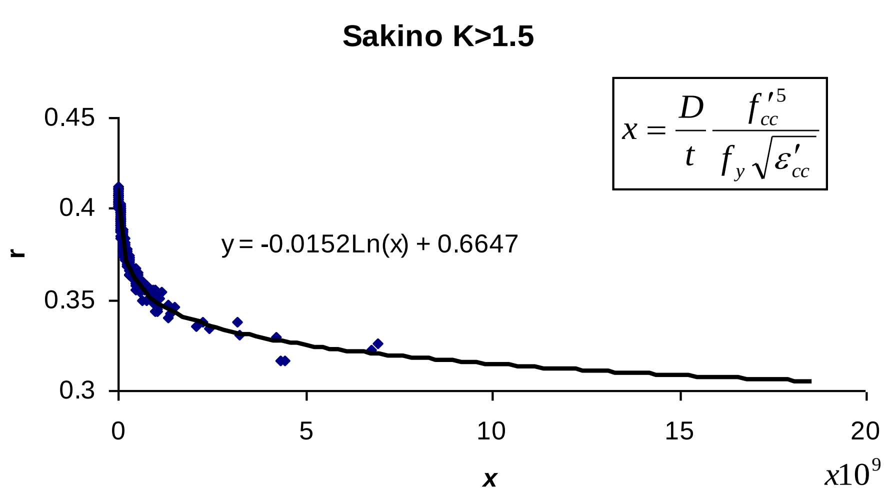

Figure 2: *r* parameter for K greater than1.5

If K is less than 1.5, the proposed mathematical expression is given by

$$r = 2x10^{-12}\left(\frac{D}{t}\frac{f_{cc}'^{2}}{\sqrt{f_y \varepsilon_{cc}'}}\right)^2 - 10^{-6}\left(\frac{D}{t}\frac{f_{cc}'^{2}}{\sqrt{f_y \varepsilon_{cc}'}}\right) + 1.202 \quad \text{For K} \le 1.5 \tag{5}$$

Figure 3 shows the best fit curve to the r values when K is less than 1.5.

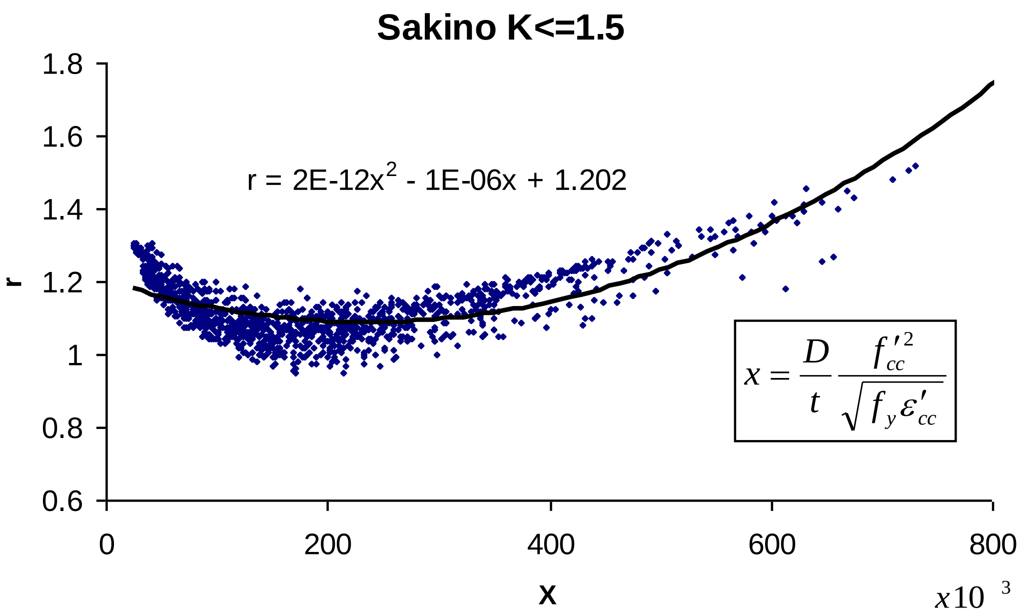

Figure 3: r *parameter for K less than or equal to 1.5*

4 Application and Verification of Proposed Model

Axial strength-strain of the test specimens are calculated by using the proposed model and compared with the test results as shown in Fig. 4. The model predicts the structural level behavior accurately.

Concrete stress distribution is not uniform over the section in the concrete-filled tube due to confinement provided by the steel. Therefore, test stress-strain data provides the local information, but it cannot be used exactly in the model prediction or verification. However, triaxial concrete cyclic test results give the average stress over the section and can be used. In the triaxial concrete test, the confinement is provided by the fluid inside the triaxial cell. The confinement provided in the triaxial cell is active confinement which is constant during the test and applied before the axial load, whereas, tube in the concrete-filled case provides passive confinement which depends on the lateral deformation of the concrete core and steel. In the high confinement scenarios, active confinement gives more strength than passive confinement, but in the low confinement scenarios both active and passive give approximately the same results (Attard et al. 1996).

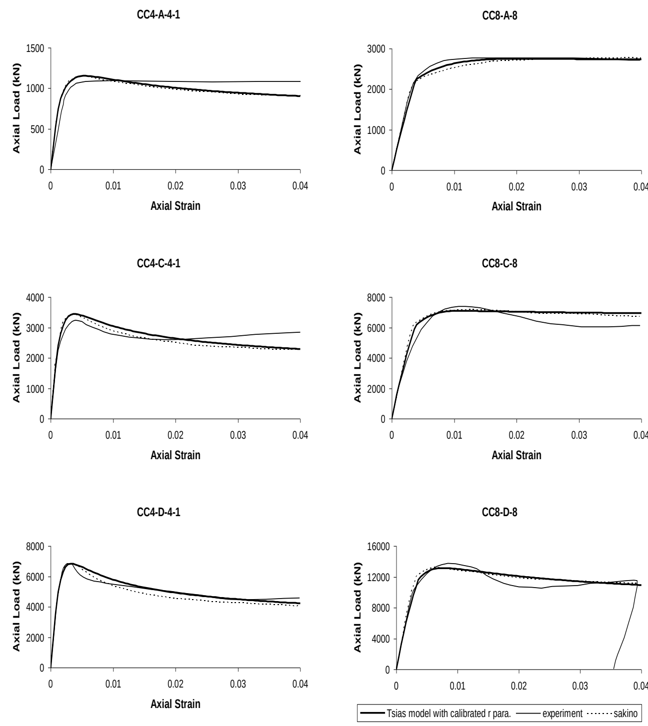

Figure 4: Axial load-strain comparison of models with experiment

The triaxial cyclic concrete results are used for verification of the envelope and cyclic curves. The model uses tube dimensions and material properties for determination of the post-peak parameter and confined strength. Therefore, pressure supplied in the triaxial cell should be the same as that of an equivalent tube. The lateral pressure provided by the triaxial cell is equated to the right hand side of the lateral pressure equation which is given in the Eq. 3. By assuming the steel properties, the thickness of the required tube to provide equivalent pressure is determined. The thickness of tube is given by

$$t = \frac{f_{lat} D}{0.38 f_y + 2 f_{lat}} \tag{6}$$

where, f_{lat} is the lateral pressure provided by the triaxial cell.

Three triaxial test results are compared with the calculated model results. The first two tests are taken from the Imran et al. (1996) and the last one from Li et al. (2002). The properties of the specimens are given in Table 1.

Table 1: Properties of the test specimens

	d *(mm)*	*f'c* *(MPa)*	*f'lat* *(MPa)*
Specimen 1	54.0	43.5	8.6
Specimen 2	54.0	64.7	38.4
Specimen 3	101.0	69.0	14.0

The calculated thickness and diameter of the equivalent tubes, and calculated confined strength of the tubes are given in Table 2.

Table 2: Calculated dimension and strength of the test specimens

	t_{eq} *(mm)*	*D* *(mm)*	*D/t*	f'_{cc} *(MPa)*
Specimen 1	4.88	63.77	13.07	80.80
Specimen 2	21.83	97.65	4.47	222.11
Specimen 3	14.88	130.76	8.78	124.14

Envelope curves of the proposed model showed a good match with the concrete-filled tube test results. Figure 5 shows the comparison of the model cyclic stress-strain results and results of the triaxial test. As seen in Fig. 5, prediction of the envelope curve is not good. The specimen sizes used in the triaxial analysis are small as compared to the concrete-filled tubes and also lateral pressure provided by the triaxial cell is more than the concrete-filled tubes. D/t_{eq} ratio is very small as compared to the concrete-filled tubes. During the test of the specimen 3, a rubber membrane was used between the fluid and the specimen. In order to consider the membrane effect, a uniaxial test was conducted for bare concrete and jacketed concrete, an average 7 percent strength increase was observed and accounted in the stress-strain record by the authors. The strength decrease after the peak is more in this specimen when compared to specimen 1, although the provided lateral pressure is large. It might be due to the fact that the rubber membrane provided more confinement at the early stage of the test and instantaneous release of the membrane at the later stage caused strength to decrease severely after the peak strength. Although the envelope curve is not predicted well for specimen 3, general pattern of the cyclic behavior predicted well by the model.

6 Conclusions

The parameters are proposed in order to use Chang and Mander's (1994) model in the analysis of concrete-filled tubes. Comparison of the test results and analysis for monotonic loading shows good agreement. Cyclic behavior of the concrete is verified by the triaxial concrete test. This might be due to the small dimension of the tested specimens and high amount of lateral pressure, meaning envelope curve prediction is not very good. On the other hand, general cyclic behavior prediction is good. In order to draw a conclusion, more test data with less confinement and bigger dimension is required.

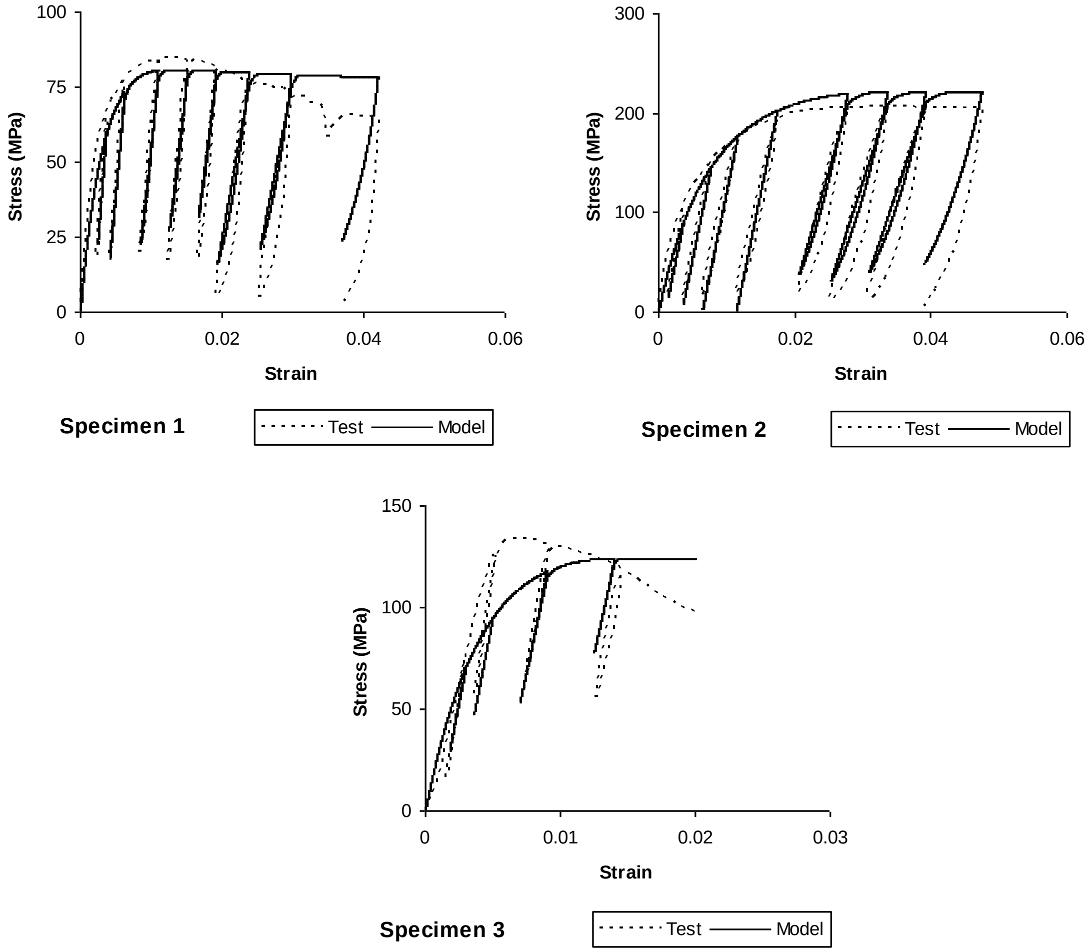

Figure 5: Comparison of cyclic stress-strain results of triaxial test and model

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