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INVESTIGATION OF STRESS-STRAIN MODELS FOR CONFINEMENT OF CONCRETE BY Welded Wire FABRIC

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Abstract

Various analytical models available in the literature for the confinement of concrete by conventional rectilinear ties and welded wire fabric are studied. These models are applied to the specimens tested by the authors as well as by other investigators to predict the results. Experimental results are compared with results predicted by various models. It is concluded that none of the analytical models could accurately predict the stress-strain curves for the full range of experimental data considered in this study. Most of the models were able to predict the peak strength but failed to predict satisfactorily the associated strain and the stress-strain curves. The predictions of the Akiyama et al. were generally in closest agreement with the experimental results. Since this model incorporates almost all the parameters of confinement.

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1. INTRODUCTION

As is well known, that confining the core of a reinforced concrete column with lateral reinforcement will significantly increase the strength and the ductility of the column. Confinement reduces the loss of strength due to spalling of the concrete cover and increases the ability of the concrete core to sustain large deformations without a dramatic loss in strength. The increase in strength and especially in ductile behavior due to confinement is extremely important for reinforced concrete building columns. The degree of confinement is related to the configuration, size and longitudinal spacing of the lateral reinforcement in the column.

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In recent years, non-conventional materials, by their ease of construction, and better quality control, have quickly appeared as innovative solutions used to avoid the congestion caused by the hooks in the stirrups and crossties. Welded wire fabric (WWF) as confining transverse reinforcement in columns is an alternative to conventional steel ties. The WWF may be placed transversely in the core of the concrete column in parallel stack with a uniform longitudinal spacing or it may be wrapped around the column in addition to conventional ties. A number of studies (Holland 1995; Hong 1997; Lambert and Tabsh 1999, 2001; Tavio et al. 2008; and Kusuma et al. 2010) have reported the behavior of concrete confined by WWF. Several analytical models with various degrees of sophistication have been proposed. All the models proposed have been developed by researchers for their own set of data. In these models, several influencing variables have been considered, including the diameter, spacing, and yield strength of the lateral reinforcement, distribution of longitudinal steel and the resulting tie configuration, and section dimensions.

In this paper the available analytical models (Hoshikuma et al. 1997; Razvi and Saatcioglu 1999; Legeron and Paultre 2003; Akiyama et al. 2010) are applied to predict the results of tests reported by the authors as well as by other investigators (Holland 1995; Hong 1997; and Lambert and Tabsh 1999, 2001). The predictions of the Akiyama et al. were generally in closest agreement with the experimental results.

2. EXISTING CONFINEMENT MODELS

The analytical model presented in this paper provides a means of predicting the behavior of axially loaded concrete columns that have been confined using steel ties. Almost all the analytical models for conventional confinement were developed on the basis of the observations in the experimental studies. The success of an analytical model is largely rooted in its ability to describe the material behavior of all elements in the system accurately. Confined concrete columns have two main elements: concrete and confining devices. Accurate models for confined concrete behavior have already been established (e.g., Kent and Park (1971); Sheikh and Uzumeri (1982); and Mander et al. (1988)) that have substantiated by the work of many researchers. Consequently, the current challenge in modeling confined column behavior is the ability to describe the behavior of the confining elements themselves, as well as their interaction with the column response.

Typically, confinement for concrete columns is provided using transverse steel reinforcing bars (ties), but recent research has focused on new confinement using welded wire fabric. The analytical models proposed by Hoshikuma et al. (1997), Razvi and Saatcioglu (1999), Legeron and Paultre (2003), and Akiyama et al. (2010) are used in this paper for comparison with the results of tests reported by various researchers. All of the available analytical models can be employed for conventional confinement configurations.

Hoshikuma et al. (1997) developed a new model after observing that a second order parabola for the ascending branch can reflect only three boundary conditions of the four boundary conditions which should be reflected by the ascending branch of the stress-strain curves. This model is applicable to normal strength concrete columns based on the results of a series of compression loading tests of reinforced concrete columns specimens and suggested a new one that is applicable for bridge piers.

Razvi and Saatcioglu (1999) modified the stress-strain relationship of confined concrete applicable to columns with high-strength concrete, which was proposed earlier for normal-strength concrete by them (1992). It was also applicable to concretes confined by spirals, rectilinear hoops, crossties, welded wire fabric, and combinations of these reinforcements. It incorporated the effect of high-strength transverse reinforcement, with up to yield strength of 1400 MPa or lower.
Legeron and Paultre (2003) proposed a stress-strain model for confined concrete based on strain compatibility and transverse force equilibrium. The model is an expansion of a proposal by Cusson and Paultre (1995) which was developed for high strength concretes.

Recently, Akiyama et al. (2010) proposed a stress-averaged strain model for confined concrete using the effective confinement pressure and the compressive fracture energy. This model is applicable to columns with either circular or square sections made of concrete having compressive strengths up to 130 MPa and transverse reinforcement having yield strengths up to 1450 MPa.

3. COMPARISONS WITH EXPERIMENTAL RESULTS

The available experimental data of Holland (1995), Hong (1997), and Lambert-Aikhionbare (1999, 2001), and tests reported by Authors (2011) in a companion paper were used as a basis for comparison of the accuracy of the stress-strain curve predictions of various models proposed in the literature (Hoshikuma et al. (1997), Razvi and Saatcioglu (1999), Legeron and Paultre (2003), and Akiyama et al. (2010)). Table 1 summarizes the dimensions, number, concrete strength, spacing, volumetric ratio, arrangement of welded grid, and strength of WWF-confining reinforcement of each specimen and the gauge length used to measure deformation.

Table 1: Details of specimens tested by authors and other investigators

<table>
<thead>
<tr>
<th>Reference</th>
<th>Section dimension (mm)</th>
<th>Number</th>
<th>Height (mm)</th>
<th>Gauge length (mm)</th>
<th>$f'_c$ (MPa)</th>
<th>Transverse reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holland (1995)</td>
<td>127 x 127</td>
<td>62</td>
<td>381</td>
<td>152.4</td>
<td>42.6-44.9</td>
<td>$\sigma$, $f_yh$, $\rho_s$ (%)</td>
</tr>
<tr>
<td>Hong (1997)</td>
<td>127 x 127</td>
<td>24</td>
<td>381</td>
<td>152.4</td>
<td>50.6-56.4</td>
<td>12.7-31.75, 1.23-4.30, 288-490</td>
</tr>
<tr>
<td></td>
<td>356 x 356</td>
<td>6</td>
<td>1524</td>
<td>610</td>
<td>52.6-59.4</td>
<td>25.4-50.8, 2.40-3.80, 440</td>
</tr>
<tr>
<td>Lambert-Aikhionbare (1999)</td>
<td>356 x 356</td>
<td>10</td>
<td>1524</td>
<td>610</td>
<td>62-76</td>
<td>44-95, 3.5-5.00, 490</td>
</tr>
<tr>
<td>Authors (2010)</td>
<td>180 x 180</td>
<td>18</td>
<td>720</td>
<td>320</td>
<td>43.4</td>
<td>30-120, 1.2-4.80, 500</td>
</tr>
</tbody>
</table>

Note: * see Fig. 1

The proposed model is used to predict results from 120 concentrically loaded, small- or large-scale columns with concrete strengths ranging from 40 to 75 MPa and yield strengths of WWF-confining reinforcement ranging from 288 to 576 MPa. The comparisons of the models predictions and the experimental results are presented in three categories, i.e. the comparisons for peak strength and strain, the post-peak strain at 85 percent of peak strength, and those for the complete stress-strain curves.

The purpose of the research program by Holland (1995) was only concentrated in investigating the effect of to dimensional WWF with various vertical spacing in the specimens, no contribution of longitudinal reinforcement and concrete cover were included (see Fig. 1, arrangement type A, B, and C, respectively).

The reliability evaluation of the analytical models was based on the computation of the statistics of three key parameters (i.e. the maximum confined concrete strength, $f'_c$; the confined concrete strain at the maximum strength, $\varepsilon_{cc}$; and the strain along the descending branch of the confined stress-strain curve when the stress drops to 85 percent of the maximum confined concrete strength, $\varepsilon_{cc,85}$). A brief statistical analysis was conducted. The results include the mean, standard deviation, and coefficient of variation, respectively, between the predictions by various models and the experimental data. Table 2 illustrates the statistics obtained for the three parameters for each analytical model alongside the number of specimens considered each time.
Table 2: Statistics of the ratio of experimental to analytical values for three key parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>Statistics</th>
<th>$f_{cc}$</th>
<th>$\varepsilon_{cc}$</th>
<th>$\varepsilon_{cc \text{ HS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoshikuma et al. (1997)</td>
<td>Mean</td>
<td>1.17 (120)</td>
<td>1.09 (117)</td>
<td>1.15 (116)*</td>
</tr>
<tr>
<td></td>
<td>St. Dev.</td>
<td>0.12 (120)</td>
<td>0.50 (117)</td>
<td>0.47 (116)*</td>
</tr>
<tr>
<td></td>
<td>COV (%)</td>
<td>10.11 (120)</td>
<td>45.57 (117)</td>
<td>40.95 (116)*</td>
</tr>
<tr>
<td>Razvi &amp; Saatcioglu (1999)</td>
<td>Mean</td>
<td>0.98 (120)</td>
<td>1.02 (117)</td>
<td>0.66 (116)</td>
</tr>
<tr>
<td></td>
<td>St. Dev.</td>
<td>0.15 (120)</td>
<td>0.75 (117)</td>
<td>0.68 (116)</td>
</tr>
<tr>
<td></td>
<td>COV (%)</td>
<td>15.20 (120)</td>
<td>73.31 (117)</td>
<td>103.01 (116)</td>
</tr>
<tr>
<td>Legeron &amp; Paultre (2003)</td>
<td>Mean</td>
<td>1.17 (120)</td>
<td>1.58 (117)</td>
<td>1.52 (116)*</td>
</tr>
<tr>
<td></td>
<td>St. Dev.</td>
<td>0.10 (120)</td>
<td>0.67 (117)</td>
<td>0.55 (116)*</td>
</tr>
<tr>
<td></td>
<td>COV (%)</td>
<td>8.67 (120)</td>
<td>42.23 (117)</td>
<td>36.35 (116)*</td>
</tr>
<tr>
<td>Akiyama et al. (2010)</td>
<td>Mean</td>
<td>0.94 (120)</td>
<td>0.62 (117)</td>
<td>0.66 (116)*</td>
</tr>
<tr>
<td></td>
<td>St. Dev.</td>
<td>0.09 (120)</td>
<td>0.25 (117)</td>
<td>0.34 (116)*</td>
</tr>
<tr>
<td></td>
<td>COV (%)</td>
<td>9.59 (120)</td>
<td>40.53 (117)</td>
<td>51.61 (116)*</td>
</tr>
</tbody>
</table>

St. Dev.: Standard Deviation, COV: Coefficient of Variation.
*: Interpolated value

3.1. Peak strength and strain

Figures 2 - 3 show the various models’ comparisons of the predicted peak strengths and strains with the experimental values. The uncertainty related to the predicted confined concrete strength was found to be relatively low for all models, the coefficient of variation ranging from 8.7 to 15.2 percent (Table 2). Scatter diagrams for $f_{cc}$ are shown in Fig. 2. On the other hand, the uncertainty in the prediction of the second selected key parameter which involves the strain at peak stress of confined concrete was found to be relatively high. Scatter diagrams for $\varepsilon_{cc}$ are shown in Fig. 3. The coefficient of variation of the peak strain ranges from 40.5 to 73.3 percent, on the basis of 117 specimens.

The model proposed by Hoshikuma et al. (HKNT) under-predicted the peak stress for the all the experimental data considered (Fig. 2(a)), and under-predicted the experimental strain at peak for both Hong’s and Lambert’s data, respectively (Fig. 3(a)). The under-predictions increased as the compressive strength and the amount of confinement increased.

For Legeron and Paultre (LP) model, both peak stress and strain at peak were under-predicted for all the experimental data considered (Figs. 2(c) and 3(c), respectively). The predicted peak strains for Hong’s and Lambert and Tabsh’s data were generally too high. The strains for both Holland’s and Authors’ data, respectively, were better predicted, although they were generally slightly lower than the experimental peak strains. The Legeron and Paultre (LP) model which recognizes confinement with normal and high yield steel underestimated the confined concrete strength by 17 percent and the uncertainty in this case was found to be 8.67 percent.
The model proposed by Razvi and Saatcioglu (RS) slightly over- or under-predicted the experimental peak stress results of Holland and Lambert and Tabsh (Fig. 2(b)). The peak stress for Authors’s data was over-predicted or only slightly under-predicted. The strains at the peak followed the same trend (Fig. 3(b)). The proposed equations by Razvi and Saatcioglu (RS) derived from the statistical analysis predict the experimental values of peak strength and strain was higher uncertainty than the other models, as seen
in Table 2. The coefficients of variation of the strength and strain at peak stress are of 15.2 and 73.3 percent, respectively.

Generally, the peak stress was predicted very well by the model proposed by Akiyama et al. (ASF), Fig. 2(d). The under- and over-prediction of peak stress were minimal, which give uncertainty of 9.5 percent. The prediction of the strain at peak did not correlate well with the experimental results (Fig. 3(d)): the predicted peak strains for almost data were generally too high.

### 3.2. Ductility evaluation

The ductility of the column depends greatly on the confinement degree of the core concrete. This study measured the ductility of the specimen by utilizing the definition of the ductility ratio provided by Razvi and Saatcioglu (1994). The ductility ratio \( \mu \), which is the ratio of the core concrete strain \( e_{cc85} \) corresponding to the stress \( 0.85 f'_{cc} \) on the descending branch to the unconfined strain at the peak stress \( (e_{cc}) \). The comparison at post-peak is only made at strain of 85 percent of peak stress. Table 2 show the ratios of these predicted to experimental post-peak strains.

Figure 4: Scatter diagrams for peak strain \( e_{cc85} \). (L&T = ‘Lambert and Tabsh’)

The uncertainty in the prediction of the ultimate strain, \( e_{cc85} \) was found to be relatively high (Fig. 4). The coefficient of variation of the ultimate concrete strain corresponding to \( 0.85 f'_{cc} \) along the descending branch of the stress-strain curve ranges from 36.3 to 103 percent, on the basis of 116 specimens. The good mean values yielded by the Hoshikuma et al. (HKNT) model, as well as the mean values of Legeron and Paultre (LP) model for \( cc85 \) if compared to the other models.

### 3.3. Stress-strain curves of confined concrete
Selected comparisons of analytical and experimental stress-strain curves for eight specimens with different grids configurations are given in Fig. 5. It can be seen that significant scatter exists in the post-peak range. Stress-strain curves predicted by models of Hoshikuma et al. (1997), Razvi and Saatcioglu (1999), Legeron and Paultre (2003) and Akiyama et al. (2010) are denoted by HKNT, RS, LP and ASF, respectively, while EXP is ‘experimental’.) The stress-strain curves obtained from the analytical models were examined to see how well each model predicted the pre-peak and post-peak behaviors of the experimental stress-strain curves of RC columns confined by WWF.

Figure 5: Comparison of experimental and predicted stress-strain curves.

The pre-peak behavior of stress-strain curves predicted by all models considered agrees well with the experimental stress-strain curves (Fig. 5), except for the Hoshikuma et al. (1997) model was slightly less steep (lower stress) than the experimental curve. The comparisons for eight specimens of the post-peak range. Stress-strain curves predicted by models of Hoshikuma et al. (1997), Razvi and Saatcioglu (1999) and Akiyama et al. (2010) are denoted by HKNT, RS, LP and ASF, respectively, while EXP is ‘experimental’.) The stress-strain curves obtained from the analytical models were examined to see how well each model predicted the pre-peak and post-peak behaviors of the experimental stress-strain curves of RC columns confined by WWF.

From the comparisons (Fig. 5) it appears that although none of the analytical models could accurately predict the full range of the experimental data considered in this study, the predictions of Akiyama et al. were generally in closest agreement with the experimental results.

4. CONCLUSIONS

A comparative study is undertaken to evaluate the capabilities of the various confinement models to predict the actual experimental behavior. The study indicated that almost all the models are able to estimate correctly ascending part of stress-strain curve. However, there are wide variations in the prediction of the post-peak part of stress-strain curves, with a few models underestimating and overestimating the test behavior. Therefore, the present study concludes that none of the available analytical models could accurately predict the stress-strain curves for the full range of experimental data considered in this study. Although none of the analytical models could accurately predict the full range of the experimental behavior, the predictions of the Akiyama et al. were generally in closest agreement with the experimental results.

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