Behaviour of Concrete Confined with Composite Materials

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ABSTRACT
Many structures collapsed in recent earthquakes highlighted the need for the strengthening of these existing structures. The need arises because of the inadequate lateral strength and ductility of these old structures. Basically these old structures were primarily designed to resist gravity loads. The introduction of composite materials and its innovative applications in engineering is relatively recent in origin. More recently, the interest in using composite material for confinement of new or existing concrete columns, has led to the attention of researchers and of the industry on its applications in civil engineering. During the last 2 decades, number of analytical models has been presented in literature to predict the stress-strain behaviour of concrete confined by composite wraps. These models have generally derived from the experimental data, but it is difficult to find a model which yields the most accurate results. For design of any member, along with the other properties, its stress-strain behaviour is of utmost importance. A detailed comparison has been carried out on the stress-strain behaviour of concrete strengthened with composites.

Keywords— Columns, Composites, Concrete, Confinement, Fibre Reinforced Polymers

I. INTRODUCTION
It is well established fact that confining the concrete increases strength and ductility. One of the methods of achieving improvement in strength and ductility is confining the concrete by composite materials. The non-corrosive nature, light weight, high strength, high fatigue resistance, low thermal conductivity, bad conductor of electricity, non-magnetic nature, and ease installation gives added advantages over the conventional confining reinforcing material (i.e. steel). The composite fibre system is a non-intrusive structural strengthening system that increases the load carrying capacity, (shear, flexure, and compressive) and ductility of concrete members without causing any destruction or distress to the existing concrete. A significant research has been carried out on the use of composite composites for confinement of concrete. During the last two decades, a number of analytical models have been presented in literature to predict the stress-strain behaviour of concrete confined by composite materials. These models have generally derived from the experimental data, but it is difficult to find a model which yields the most accurate results. For design of any member, along with the other properties, its stress-strain behaviour is of utmost importance. The paper deals with carbon composites confined circular columns under concentric axial load.

II. METHODOLOGY
This paper attempts to study comparison of the various models taken from literature on composite confined concrete. The study has been undertaken so as to find out the best fit model for carbon composite confined circular columns under concentric axial load. For this a total of five models on composite confined concrete and five experimental test results have been selected.

III. CONFINEMENT OF CONCRETE WITH COMPOSITE MATERIALS
Various studies have been carried out on confinement of concrete steel ties or by spiral steel reinforcement. Few studies have investigated the role of longitudinal reinforcement in providing confinement. Confinement of concrete by steel pipes or plastic pipes has been reported in literature. The findings have confirmed that both strength and ductility increases with an increase in confining pressures offered by steel ties, steel pipes, and plastics pipes, etc. This section describes in brief the confinement models considered for this paper.

Richart et al. [1] were among the first to propose a confinement model for concrete. They developed an empirical formula to quantify the increase in the concrete compressive strength due to the application of a constant triaxial pressure. The authors proposed the following relation for stress enhancement of confined concrete:

\[ f'_{cc} = f'_{co} + k_1 f_l \]  

(1)

Whereas, the following relation has been proposed for the prediction of strain at peak stress:

\[ \varepsilon_{cc} = \varepsilon_{co} \left( 1 + k_2 \frac{f'}{f''_{co}} \right) \]  

(2)
Fardis and Khalili [2, 3] are believed to be the first applicators of composite material for confinement of concrete. Compression tests were conducted on several 3 x 6 in. and 4 x 8 in. (75 x 150 and 100 x 200 mm) concrete cylinders, encased in four different types of composites. The results of the 3 x 6 in. cylinders strength wrapped with composite showed agreement with the failure envelopes of concrete under the action of axial stress $f'_{cc}$ and lateral pressure $f_l$ as suggested by Richart et al. (1928):

$$\frac{f'_{cc}}{f_{co}} = 1 + 4.1 \frac{f_l}{f_{co}} \tag{3}$$

$$f_l = \frac{2f_{fp}nt_{fp}}{D} \tag{4}$$
i.e., the maximum confinement pressure that the composite can exert before rupturing in tension. Therefore, the model by Fardis and Khalili can be summarized as follows:

$$\frac{f'_{cc}}{f_{co}} = 1 + 4.1 \left( \frac{2f_{fp}nt_{fp}}{f'_{co}D} \right) \tag{5}$$

Whereas the following proposals were made for the prediction of strain $\varepsilon_{cc}$ at peak stress and axial stress-strain relationship:

$$\varepsilon_{cc} = \varepsilon_{co} + 0.001 \left( \frac{f_{fp}nt_{fp}}{f'_{co}E_{cc}} \right) \tag{6}$$

$$f_c = \frac{E_{co}\varepsilon_c}{1 + \varepsilon_c \left( \frac{E_{co}}{f_{co}} - 1 \right) \varepsilon_{cc}} \tag{7}$$

Karbhari and Gao [4] model was based on composite analysis and resulted in the following equations for stress and strain at ultimate:

$$f'_{cc} = f'_{co} + 3.1f'_{co}\varepsilon_c \frac{2f_{fp}E_{fp}}{d} + \frac{2f_{fp}f_{fp}}{d} \tag{8}$$

$$1.004 \left( 1 - \frac{f'_{co}}{E_{fp}} - 4.1f'_{co}\varepsilon_c \frac{2f_{fp}}{d} \frac{E_{fp}}{E_{eff}} \right) \frac{f'_{cc}}{f_{co}} = 1 - \frac{f_{fp,rup}}{E_{fp}} \tag{9}$$

Miyachi et. al. [5] proposed the following equation to estimate the strengthening effect of the composite confinement:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 4.1 \varepsilon_e \left( \frac{2f_{fp}nt_{fp}}{f'_{co}} \right) \tag{10}$$

for the computation of $\varepsilon_{cc}$ two empirical equations were suggested:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 10.6 \left( \frac{f'_l}{f'_{co}} \right)^{0.273} \text{ for } f'_{co} = 30 \text{ MPa} \tag{11}$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 10.5 \left( \frac{f'_l}{f'_{co}} \right)^{0.525} \text{ for } f'_{co} = 50 \text{ MPa} \tag{12}$$

which were calibrated using the experimental values of $\varepsilon_{co}$.

The complete stress-strain relationship of the confined concrete was proposed based on the observed behaviour as consisting of a parabolic branch modeled by the same equation of the unconfined concrete, followed by a straight line tangent to the parabola at the intersection point:

$$f_c = f'_{co} \left[ 2 \left( \frac{\varepsilon_c}{\varepsilon_{co}} \right) - \left( \frac{\varepsilon_c}{\varepsilon_{co}} \right)^2 \right] \text{ for } (0 \leq \varepsilon_c \leq \varepsilon_t) \tag{13}$$

$$f_c = f'_{cu} - \lambda (\varepsilon_{cu} - \varepsilon_c) \text{ for } (\varepsilon_c \leq \varepsilon_c \leq \varepsilon_{cu}) \tag{14}$$

where: $\varepsilon_t = \varepsilon_{co} - \frac{\lambda E_{cc}}{2f'_{co}} \tag{15}$

and:

$$\lambda = \left\{ -2f'_{co}(\varepsilon_{cu} - \varepsilon_{co}) + 4f'_{co}(f'_{cc}E_{cc}^2 - 2f'_{co}\varepsilon_{cu}f'_{cc} + f'_{cc}\varepsilon_{co}) \right\}^{0.5} \frac{E_{cc}}{f'_{co}} \tag{16}$$

Lam and Teng [6, 7] observed that the average hoop strain in composite at rupture in composite wrapped concrete is much lower than the composite material ultimate tensile strain from flat coupon tests, which indicates the assumption that composite ruptures when the composite material tensile strength reach is not valid in the case of concrete confined by composite wraps. As a result, instead of using composite material ultimate tensile strain $f_{fp}$, actual hoop strain at composite rupture $\varepsilon_{h,rup}$ has been used. Thus the actual maximum confining pressure is given by

$$f_{1,a} = \frac{2E_{fp}f_{fp}\varepsilon_{h,rup}}{d} \tag{17}$$

and the expression for the ultimate strength of confined concrete is given by

$$\frac{f'_{cc}}{f_{co}} = 1 + 3.3 \frac{f_{1,a}}{f'_{co}} \tag{18}$$

The proposed stress-strain model for composite confined concrete is given by the following expressions:

$$f_c = E_c\varepsilon_c - \frac{(E_c - E_2)\varepsilon_c^2}{4f_o} \text{ for } (0 \leq \varepsilon_c \leq \varepsilon_{co}) \tag{19}$$

$$f_c = f_o + E_2\varepsilon_c \text{ for } (\varepsilon_c \leq \varepsilon_c \leq \varepsilon_{cu}) \tag{20}$$

where $f_o$ is the intercept of the stress axis by the linear second portion. The parabolic first portion meets the linear second portion with a smooth transition at $\varepsilon_t$ which is given by

$$\varepsilon_t = \frac{-2f_o}{E_c - E_2} \tag{21}$$

where $E_2$ is the slope of the linear second portion, given by

$$E_2 = \frac{f'_{cc} - f_o}{\varepsilon_{cu}} \tag{22}$$
For the case of composite confined concrete efficiency factor of 0.586 has been specified.

IV. COMPARISON OF ANALYTICAL AND EXPERIMENTAL STRESS-STRAIN BEHAVIOUR

Many tests have been conducted on composite confined concrete and also predictive models have been proposed for the uniaxial stress-strain curve. Very few of the researchers have tried to compare the confinement models with respect to the experimental stress-strain curve. In this section an attempt has been made to investigate the relative performance of the various proposed analytical models with regard to the capabilities of producing the experimentally observed stress-strain profiles on different test specimens. All together five test specimens were chosen from the literature to carry out the comparative study. All the test specimens were of circular cross section and of normal strength concrete. Table 1 gives details of test specimens and its source. Computer programs were written for all the models of the study and using these programs uniaxial stress-strain curves for each of the chosen test specimens corresponding to all models were predicted. Table 2 gives the ratio of predicted ultimate confined concrete strength to respective experimental ultimate confined strength. The corresponding ratios for ultimate confined concrete strain are shown in table 3. Fig. 1 to 5 gives the uniaxial stress-strain curve obtained using the various models. The stress-strain curves from fig. 1 to 5 appear in the order in which the experimental test specimens appear in table 1. In addition to the prediction of uniaxial stress-strain curve computations were carried out for the ultimate confined stress $f_{cc}'$ and the corresponding strain $\varepsilon_{cc}$. The difference between the two models by Lam & Teng [6] is that in the case of model (a) the estimated composite strain has been considered while in case of model (b) the strain was the actual composite strain.

### TABLE 1. SPECIMEN DETAILS

<table>
<thead>
<tr>
<th>Source of data</th>
<th>Specimen</th>
<th>$d$ (mm)</th>
<th>$l$ (mm)</th>
<th>$f_{cc}'$ (MPa)</th>
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<tbody>
<tr>
<td>Miyauchi</td>
<td>C1</td>
<td>100</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>100</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Lam &amp; Teng</td>
<td>C1-1</td>
<td>152</td>
<td>305</td>
<td>35.9</td>
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<tr>
<td></td>
<td>C2-1</td>
<td>152</td>
<td>305</td>
<td>35.9</td>
</tr>
<tr>
<td></td>
<td>C3-1</td>
<td>152</td>
<td>305</td>
<td>35.9</td>
</tr>
</tbody>
</table>

### TABLE 2. COMPARISON FOR ULTIMATE CONFINED CONCRETE STRENGTH $f_{cc}'$

<table>
<thead>
<tr>
<th>Data Source</th>
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<th>$f_{cc,exp}$ (MPa)</th>
<th>$f_{cc,pred}/f_{cc,exp}$</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>F&amp;K</td>
</tr>
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<tr>
<td></td>
<td>C2</td>
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### TABLE 3. COMPARISON FOR ULTIMATE CONFINED CONCRETE STRAIN $\varepsilon_{cc}$

<table>
<thead>
<tr>
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<th>$\varepsilon_{cc,exp}$</th>
<th>$\varepsilon_{cc,pred}/f_{cc,exp}$</th>
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<td></td>
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<td></td>
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<td>0.0144</td>
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<td></td>
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<tr>
<td></td>
<td>C2-1</td>
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<tr>
<td></td>
<td>C3-1</td>
<td>0.0225</td>
<td>1.058</td>
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</table>

Figure 1. Comparison of stress-strain behaviour with respect to specimen C1 data

Figure 2. Comparison of stress-strain behaviour with respect to specimen C2 data
IV. PERFORMANCE OF CONFINEMENT MODELS

The mean error has been employed to quantify the performance index of the various confinement models under this study. The study focused to check the relative performance of models to predict the uniaxial compressive strength.

Model by Fardis and Khalili over estimate the ultimate strength of composite confined concrete for almost all the experimental test values, with a mean error of 33.91%. The model of Karbhari and Gao II under estimates the ultimate strength. The model by Miyauchi et al and Lam & Teng (a) (b) predicts mean error of approximately 14 to 15% for $f_{cc}$. The model by Lam & Teng (a) is observed to be conservative.

Karbhari & Gao II, model over estimates the ultimate strain of composite confined concrete for almost all the experimental test values. Fardis and Khalili’s model has also a higher value of mean error but for most of the cases it underestimates the ultimate strain values. Except the model by Miyauchi et al. the other models have closer value of mean error but only the model by Lam & Teng (a) & (b) are conservative in predicting the ultimate strength while others have mix response. Miyauchi et al. model’s prediction for ultimate confined concrete strain has a least mean error compared to other models under consideration, with a mean error value of 15.74%.

V. CONCLUSION

A number of empirical equations have been proposed to calculate the ultimate strength and strain of composite confined concrete. In this paper several confinement models were studied to find the best fit model for composite confined concrete.

- The model by Lam & Teng (a) & (b) are conservative in predicting the ultimate strength with a value of 11.86% and 14.49%, respectively.
- Miyauchi et al. model’s prediction for ultimate confined concrete strain has a least mean error with a value of 15.74%.
- From the various models considered under the present study for the comparison, it has been observed that the model by Miyauchi et al. predicts well the ultimate strength and strain of composite confined concrete.

REFERENCES