EFFECT OF CARBON FRP IN CONFINING CIRCULAR RC COLUMNS USING ARTIFICIAL NEURAL NETWORKS

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ABSTRACT: Structural experiments have shown that passive confinement due to carbon fiber-reinforced polymers (CFRPs) enhance the ultimate compressive strength and ductility of RC circular columns. The accurate prediction on the effect of the CFRP in its ultimate confined compressive strength of RC columns is very vital in designing the strength capacity of a structure. Since experimental data on confined RC columns are readily available in literatures, it may be useful to combine and reanalyze them to develop empirical models that can give reasonable predictions of the ultimate confined compressive strength of RC columns. However, the many factors which affect the ultimate confined compressive strength of RC columns makes modeling for predicting difficult and complex especially when pre-existing transverse steel reinforcements and together with CFRP are used as confining materials. The effect of various parameters such as $\rho_s$, $\rho_{cc}$, $\rho_{CFRP}$, $L$, $d$, $D$, $fyh$, $f_{CFRP}$, and $f'_c$ are considered in the development of ANN models. The study presents artificial neural networks (ANNs) in modeling to determine the effect of CFRP in the ultimate compressive strength of circular RC column.

KEYWORDS: Confined Concrete, Steel Ties, Carbon Fiber Reinforced Polymer, Artificial Neural Networks, Compressive Strength

1. INTRODUCTION

The confinement of concrete by transverse steel reinforcement improves the strength and ductility of reinforced concrete (RC) columns and bridge piers. The advantages of confinement in improving the performance of RC columns have been recognized in modern structural design codes especially in seismic design. Seismic codes specify special provisions for concrete such as the minimum requirements of the amount and spacing of transverse reinforcement, including critical locations where transverse reinforcement should be placed.

Nowadays, fiber-reinforced polymers (FRPs) have started to be used as confining materials in structures. It has high strength-to-weight ratio, high confinement strength, easy to install and maintain, fatigue resistant, non-magnetic, non-metallic, and durable. With respect to rehabilitation, strengthening and retrofitting of existing and deteriorated structures, FRP sheets have now become very popular devices in enhancing the performance of existing RC columns. RC columns that are confined by both steel reinforcement and FRP, which are sometimes referred to as “hybrid RC columns”, have now become common in existing buildings and bridges.

Three types of FRP are commonly used. These are aramid fibers, glass fibers, and carbon fibers (CFRPs). This paper only considers carbon fiber reinforced polymers (CFRPs) due to its ideal properties compared to glass fibers and aramid fibers. From studies, glass fibers are weak in aging and should be protected from chemical attack. CFRPs have been proven to be more efficient than aramid and glass fibers when applied to concrete columns as external reinforcement. FRPs in general produce small increase in weight and area that tends to lead to a more economical overall project cost. Unlike steel jacket as confinement, it does not suffer from negative aspects like field welding and corrosion.
There are two ways in confining CFRPs in concrete. The wrapping of CFRPs in concrete and the CFRP tube encasing. In most experimental studies conducted, CFRP wraps were observed to rupture at a tensile strain relatively lower than the uniaxial ultimate tensile strain compared to CFRP tube encasing. This premature failure was caused by the following factors: manual lay-up technique, number of thickness of overlapping layers, elastic modulus of the wrap, and radius of curvature. Different models led to different accuracy in prediction of ultimate confined compressive strength, $f'_{cc}$, due to the methodology of their CFRP confinement. Existing models such as Samaan et.al.(1998), Saafi et.al.(1999), Spoelstra and Monti (2000) gave good predictions of the confined concrete strength, with no appreciable difference between wrapped and encased specimens. These mentioned models, however, did not consider the presence of transverse reinforcements in concrete. Hence, they cannot be used in existing columns where longitudinal and lateral steel bars are usually present.

In the study, experimental data from literatures for columns with steel ties and/or CFRP were collected. Artificial neural networks (ANNs) were developed to predict the ultimate confined compressive strength, $f'_{cc}$, of confined RC columns. The present study helps to contribute to the application of modern computing tools in modeling the complex interaction among concrete, steel ties, steel longitudinal bars, and CFRP in circular RC columns.

2. CONFINEMENT IN CIRCULAR RC COLUMNS

Steel ties as confinement are common to circular RC columns. These can be in the form of circular spiral ties, lap-splice hoops, and circular hoops. The type of lateral steel ties becomes irrelevant when the column is confined by both steel ties and CFRP. To generalize the effect of steel lateral ties, this paper assumed that ANN performs to eliminate the many forms of steel ties, since it will adapt and learn from available data.

Different mechanical properties between steel and CFRP was observed. The uni-axial stress-strain of each material shown in FIG.1 is presented. CFRPs are elastic up to failure while steel has an elastic-plastic region. These different material properties contribute to a complex interrelationship between the two confining materials when combined. In FIG.2, the geometric properties used as parameters in circular columns are shown. The position of lateral steel and longitudinal steel bars are within the core diameter, $d$, while the wrapping of CFRP in concrete is made by applying epoxy in the outer column diameter, $D$. 
The confinement of concrete columns by these materials is passive by nature. The activation of the steel and/or CFRPs depend on the lateral expansion due to axial compressive load. The lateral strain or the dilation of the column increases as the axial strain increases with increasing amount of compressive load. At the instant when concrete starts to crack due to the axial load carried by the column with both CFRP and steel ties, the steel ties and/or CFRP will experience tensile hoop stresses shown in **FIG. 3** and **FIG. 4**.

Two advantages of confinement are relevant in the seismic behavior of concrete columns. First, it increases both the compressive and shear strength capacity of concrete columns. Secondly, it reduces the slope of the descending branch of the stress-strain curve that failure occurs at a larger strain, and results to increase in ductility as seen in **FIG.5**. Specimens c-1a, c-4, and c-20, have an unconfined compressive strength of 38.51MPa, while c-17 had an unconfined compressive strength of 42.92MPa. Specimens c-4, c-17, and c-20 have the following volumetric ratio of confining material, $\rho_s = 1.24\%$, $\rho_{CFRP} = 1.336\%$, $\rho_s = 1.24\%$ and $\rho_{CFRP} = 1.336\%$, respectively.
Major parameters such as volumetric ratio of steel ties ($\rho_s$), volumetric ratio of longitudinal bars ($\rho_{cc}$), volumetric ratio of CFRP ($\rho_{CFRP}$), column length ($L$), $d$, $D$, yield strength of steel ($f_yh$), tensile strength of CFRP ($f_{CFRP}$) and unconfined compressive strength of 150mm diameter x 300mm height cylinder ($f'_c$) were considered in this study. There are two values of unconfined compressive strength of concrete. One is given as the unconfined compressive strength ($f'_c$) of a cylinder and another is the unconfined compressive strength of the actual size ($f'_{co}$) of a column. Most experiments provide these two values of unconfined strength except for Hosotani and Kawashima (1999) were $f'_c$ was not available. It can be observed experimentally that the two values are very close; hence in the absence of any information about either one of the two values, an estimate of the one of the values can be done or it may be assumed that $f'_c = f'_{co}$.

In FIG. 5, the total lateral pressure exerted by the concrete core from the dilation of the column will be resisted by the confining materials. From equilibrium, Eqn.(1) was derived as follows:

$$fl \times d = 2f_{CFRP} \times (t \times L) + 2f_yh \times (As)$$  \hspace{1cm} (1)

where:
- $fl$ - total lateral pressure by both confining materials
- $f_{CFRP}$ - tensile strength of CFRP
- $f_yh$ - yield strength of steel ties
- $As$ - cross sectional area of steel ties
- $t$ - thickness of CFRP
- $d$ - core diameter of concrete
- $L$ - length of column

FIG. 6 Free Body Diagram of the Confined Section
The total lateral pressure should then be multiplied by a concrete strength enhancement coefficient, $k$, to produce the effective total lateral pressure. In theory the $f'_{cc}$ is given in Eqn.(2) below.

$$f'_{cc} = f'_{co} + k f_l$$  \(\text{(2)}\)

In existing empirical models such as Hosotani and Kawashima(1999), and Li and Fang(2004), the ultimate confined compressive strength, $f'_{cc}$, due to both confining materials is expressed as a superposition of the effect of steel ties and CFRP individually as given in Eqn.(3).

$$f'_{cc} = f'_{co} + k_1 f_{ls} + k_2 f_{CFRP}$$  \(\text{(3)}\)

where:
- $k_1$ - concrete strength enhancement coefficient due to steel alone
- $k_2$ - concrete strength enhancement coefficient due to CFRP alone
- $f_{ls}$ - effective lateral confining stress due to steel alone
- $f_{CFRP}$ - effective lateral confining stress due to CFRP alone


In this study, no assumptions on the individual strength enhancement were made to come up with the ultimate compressive strength, hence Eqn.(2) was primarily recognized by the ANNs in the modeling. While both Hosotani and Kawashima(1999), and Li and Fang(2004) followed the superposition of the strength enhancement of each materials made in Eqn.(3).

3. EXPERIMENTAL DATA

Shown in Table1 are the descriptions of the experimental data. There are three sets of data collected from references. It was categorized as follows:

- SC(steel confinement) set – data that used steel ties alone as confining material
- CC(carbon FRP confinement) set – data that used carbon FRP alone as confining material
- SCC(steel and/or Carbon FRP confinement) set – data that used both, steel ties and/or carbon FRP, as confining materials.
Different experimentation and procedures were noted for each data set. For SC set, Mander et.al.(1998b) used spiral ties, while Sakai et.al.(2000) and Sakai(2001) data used steel hoops as confinement. For CC set, both Karabinis and Rousakis(2002), and Rousakis(2001) data applied an overlap of 150-160mm. While Miyachi et.al.(1997) data used an overlap of 60mm in the outer cylinder and 40mm on the inner part. For the SCC set, Hosotani and Kawashima(1999) used an overlap of 150-160mm. While Miyauchi et.al.(1997) data used an overlap of 60mm in the outer cylinder and 40mm on the inner part. For the SCC set, Hosotani and Kawashima(1999) used steel hoops and applied slices of 10-30mm CFRP for $\rho_{CFRP} \leq 0.167$, more than that, full sheets were used with an overlap of 100mm at ends. For Li and Fang(2004), the steel ties used were steel spiral, C-shaped lap-splice, and steel hoops. In the confining of CFRP, an overlap of more than 100mm was used. Li and Fang(2004) fabricated 36 specimens for their work, but due to reference constraints, data provided were averaged values of three identical specimens leading to 12 specimens in this paper.

4. NEURAL NETWORK MODELING

Artificial Neural Network is a powerful tool in analyzing these different experimentations and material property differences. It can provide accurate solutions to predict the ultimate compressive strength, $f'_{cc}$, knowing the important parameters that affect the output target. Feed-forward backpropagation artificial neural networks were done and the parameters are as shown in Table 2. The training algorithm used was Levenberg-Marquardt (Demuth and Beale 1992). The criteria for stopping training were mean square error of 0.001, and number of epoch equal to 1000. The ANN model used 1 hidden layer having transfer function of logsigmoidal on the 1st layer, and purelinear on the last layer. The model are described as follows, 1st digit represents the number of independent input parameters, while the 2nd digit represents the number of hidden nodes, and the last digit represents the final output target. Scaling was done in feeding the data to the network.

Table 2. Parameters of Steel/CFRP-Based Confinement ANN models

<table>
<thead>
<tr>
<th>Model</th>
<th>Input Parameters</th>
<th>Output Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC9-x-1B</td>
<td>$D, d, L, \rho_0, \rho_{CC}, f_{CFRP}, f_{FRP}, f'_{co}, f'_c$</td>
<td>$f'_{cc}$</td>
</tr>
</tbody>
</table>
Thirty-two ANNs were trained and tested. The criterion for choosing the acceptable network was the Pearson product moment correlation coefficient, $R$. The $R$-value represents the linearity or closeness of the predicted value to the actual value. An $R$ equal to 1.0 means that it is a perfect fit. Since $R$ does not recognize the maximum error allowable to a model, a secondary criterion was used to limit the maximum error in prediction and that was the maximum absolute error. The network chosen to give meaningful results for the over-all data is SCC9-7-1B were the $R$ for testing is 0.9891 and maximum error in testing is 9.6 MPa.

5. COMPARISON WITH ACTUAL EXPERIMENTAL DATA

The performance of SCC9-7-1B was measured in using actual SCC data. Shown in FIG.7 and 8 are the comparisons with SCC data were used.

![FIG.7 Performance of SCC Models for Varying Over-all Thickness of CFRP Sheets and Lateral Steel Ties (Hosotani & Kawashima)](image1)

It is observed that in FIG.7, the increase in the predicted compressive strength due to CFRP is almost linear with respect to $n$, especially when the over-all thickness is larger than 0.75$t$. The predictions follow a similar trend as the experimental data. In FIG.8, on the other hand, a sudden increase in strength is observed from zero-ply of CFRP to 1-ply of approximately 9MPa to 14MPa per ply of CFRP. However, the rate of increase of the compressive strength decreases from 1-ply to 2-ply of CFRP.

![FIG.8 Performance of SCC Model for Varying Over-all Thickness of CFRP Sheets and Lateral Steel Ties(Li & Fang)](image2)
6. COMPARISON WITH OTHER EXISTING MODELS

Shown in Table 3 are the $R$ values for the acceptable ANN model SCC 9-7-1B, Hosotani et al. (1999), and Li & Fang (2004). Model SCC 9-7-1B model has the accuracy of predicting the ultimate confined compressive strength on each data set over the two available models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$R$ for Training Data</th>
<th>$R$ for Testing Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC</td>
<td>CC</td>
</tr>
<tr>
<td>SCC9-7-1B</td>
<td>0.9930</td>
<td>0.9975</td>
</tr>
<tr>
<td>Hosotani et al.</td>
<td>0.8996</td>
<td>0.9267</td>
</tr>
<tr>
<td>(1999)</td>
<td>Li &amp; Fang</td>
<td>0.9116</td>
</tr>
<tr>
<td>(2004)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. EFFECT OF CFRPs IN CIRCULAR RC COLUMNS

To visualize the SCC9-7-1B model, parametric studies were done by simulating corresponding SC data with an addition of CFRP as confinement. Shown in FIG. 9, 10, and 11 are the effects of adding CFRPs having $t=0.11$mm and $f_{FRP}=3300$MPa with respect to the geometric properties and material properties set forth from each respective references. It can be seen in FIG. 9 and 10 that there is an abrupt increase of at least 65% to 100% in $f'_{cc}$ from zero-ply to 1-ply of CFRP regardless of the spacing of lateral steel ties. However, by adding another ply of CFRP to a total of two plies, the increase was minimal. One common geometric property between the column by Mander et al. 1988b and Hoshikuma et al. 1997 is the outer diameter $D$. Both columns have relatively large outer diameter $D=500$mm for both, and core diameter, $d=438$mm and $d=500$mm respectively.

![FIG.9 Mander et al 1988b with addition of CFRP sheets as confinement](image)

(D= 500mm, d= 438mm, L= 1500mm, $\rho_{cc}=1.6\%$, $f_{ys}=340$MPa, lateral steel bar diameter= 12mm, and $f'_{c}=28$MPa)
FIG. 10 Hoshikuma 1997 with addition of CFRP sheets as confinement (D = 500mm, d = 500mm, L = 1500mm, \( \rho_{cc} = 1.01\% \), \( f_{ys} = 295\text{MPa} \), and \( f'_{c} = 28.8\text{MPa} \))

In FIG. 11 using closer tie spacing, which results to an increase in \( \rho_{s} \), led to a gradual increase in \( f'_{cc} \). On the other hand, increasing the over-all thickness of the CFRP by varying the number of CFRP ply also shows significant enhancement of compressive strength. Except for the RC column having no steel ties, an addition of 1-ply led to no increase in \( f'_{cc} \).

FIG. 11 Sakai et al 2000 with addition of CFRP sheets as confinement (D = 200mm, d = 185mm, L = 600mm, \( \rho_{cc} = 1.18\% \), \( f_{ys} = 376\text{MPa} \), and \( f'_{c} = 29.8\text{MPa} \))
In FIG. 12, the strength enhancement using eqn.(2) and (3) can be seen and compared. In eqn.(3), strength enhancement due to superposition effect of each material are less than that of the actual experimental data for 1-ply and 2-plies of CFRP. On the other hand, the ANN model SCC9-7-1B, which assumed no superposition of strength enhancement on each confining materials, but rather the total enhancement due to the interaction of both, arrived at the closest and meaningful answer.

8. SUMMARY AND CONCLUSIONS

A neural network model considering the confinement effects of steel reinforcements and CFRP on circular RC columns was developed. From the various ANN models that were trained and tested, SCC9-7-1B showed the best predictions in the enhancement of compressive strength when both materials are considered. The ANN model performs better when compared to existing empirical models. With the ANN model, simulation of pre-existing columns in retrofitting can be done using CFRP plies as confinement.

Using SCC9-7-1B model to study the effect of the increase in strength, it was observed that the effect of confinement by the two materials in enhancing the compressive strength cannot be represented by a simple superposition of effects of individual materials. A complex interaction between the lateral steel reinforcements and the CFRP exists and this needs further investigation.

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