

Comparative Study among FRP-Confined Concrete Stress-Strain Models for simulating cyclic response of Circular RC Columns

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ABSTRACT

Through the 35 years ago, numerous stress–strain models of FRP-confined concrete circular columns have been concluded to predict behaviour of FRP confined concrete under the effect of compressive axial load. In this study, most popular models and recently published models were classified. The reviewed models have been implemented into OpenSees software as uniaxial material in a form of Dynamic-Link Library file (DLL). Then, numerical simulation studies using OpenSees were executed to evaluate the performance of the implemented models in predicting the cyclic response of FRP-confined reinforced concrete (RC) circular columns, available from literature. Response characteristics such as ultimate load and the corresponding displacement were applied as accuracy measures for comparison among the examined models. The results of the examined models have led to several important conclusions.

1. INTRODUCTION

There are 88 models were developed through the last three decades to predict the axial stress–strain behaviour of fiber reinforced polymer (FRP)-confined concrete in circular sections until year 2011. They are summarized and classified by [1] to three main groups; design-oriented models, analysis-oriented models and models based on other approaches. According to their investigation in that study, models by Lam and Teng [2] and Tamuzs et al. [3] were most accurately predicted the ultimate strength and strain of FRP-confined concrete. After that, many researches have developed new models such that proposed by [4], which could predict the stress-strain behaviour of normal and high strength concrete confined with FRP. Recently, another study [5] proposed a new model for circular and rectangular columns based on a large database.

Few studies have been attempted to examine the ability of using available stress strain-models of FRP-confined concrete to simulate the performance of FRP-RC columns subjected to both axial and lateral loading. OpenSees [6] is one of the famous software used in the last years to simulate the seismic performance of RC columns. It is an open source platform with high compatibility with many programming languages such as C, C++ and FORTRAN languages, and it has a well-developed fiber section for elements. This method can be cope with nonlinear structural analysis. The studies adopting OpenSees or other softwares to predict the performance of concrete columns confined with FRP under cyclic loading, have been nominated their previously proposed stress-strain models of FRP-confined concrete as [7], [8], other studies such as [9] modified the stress-strain model proposed by [2]. In these
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studies, they concluded that the selected model exhibits a good agreement to predict behaviour of RC column confined with FRP. To the authors’ knowledge, no researches compare among several of the available stress-strain models for simulation of FRP-RC columns. Moreover, in these studies, the definition of FRP rupture in the simulate results to define ultimate load and corresponding lateral displacement is not clear. Therefore, this study aims to using several stress-strain models available from literature to simulate the cyclic performance of experimental tested column.

2. STRESS-STRAIN MODELS

This study included ten models of FRP-confined concrete, some are popular such as ACI440.2-08 design code model [10], Samaan et al. (1998) [11], Hosotani and Kawashima (1999) [12], and Teng et al. (2009) [13]. In addition to a model for two-parabolic curve modelled by Harajli (2006) [14], and a model has been investigated based on size effect as Chastre and Silva (2010) [15]. Fahmy and Wu (2010) model [16] proposed based on a concept of the same lateral stiffness of RC columns confined with different types of FRP is studied, and a model for RC columns confined with FRP-tube proposed by Rousakis et al (2012) [17, 18] were also examined. Model proposed by Song et al. (2012) [19] was also included, that model has been established based on modifying some parameters of Lam and Teng model [2]. Ultimately, the last one is Lim and Ozbakkaloglu (2014) model [5], which was developed based on a large database of concrete cylinders confined with FRP sheet and tubes. The selected models have been classified into three groups according to shape of the stress-strain model and transition point. The first group (A) has a parabolic curve from the start point to the ultimate stress [11, 15]. The second group (B) consist of two branches, the first is parabolic curve and the second branch is linear, group (B) have a smooth curve at the transition point between the two branches (i.e. this point has the same tangent from left or right) ([12, 10, 13, 16 and 19]). The third group (C) has two branches, where the first branch is curve and the second would be curve or linear; and the transition point between the two branches is not smooth. Harajli model [14] is one model of group (C), and also [5] and [17, 18] are models of this group. But [5] and [17, 18] were developed to define the ultimate conditions of FRP-confined concrete with FRP sheets or FRP tubes, respectively, and thus the authors adopted the “Concrete01” model, which is originally a part of the material library of OpenSses, to simulate the behaviour of FRP-confined concrete. Concrete01 model is matching with the group (B), but the transition point is not smooth.

3. TEST COLUMNS

The tested experimental column confined with FRP under cyclic lateral load was selected based on testing under conduction of single curvature bending [7]. The details of the chosen column are cleared in Table 1. This column was tested under constant axial load was 185 kN. In addition, this column was reinforced with longitudinal steel bars with details and yield stress as 12Φ16 and (374 MPa) respectively. Lateral confinement with steel stirrups was neglected in this study. For more details of this column, readers are referred to the original reference [7].

Table 1 properties of experimental collected column [7].

<table>
<thead>
<tr>
<th>Ref</th>
<th>Column name</th>
<th>Dimension</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallardo-Zafra and</td>
<td>B2</td>
<td>D (mm)</td>
<td>H (mm)</td>
</tr>
<tr>
<td>Kawashima (2009) [7]</td>
<td></td>
<td>30</td>
<td>400</td>
</tr>
</tbody>
</table>

f_co is the unconfined concrete compressive strength, D is diameter of column, H is shear span, and Co is clear concrete cover. The tension stress of FRP, modulus of FRP and ultimate strain are f_j, E_j, ε_j respectively. T_j is the thickness of FRP at plastic hinge region (1000 mm from column base).

It was reported by Gallardo-Zafra and Kawashima (2009) [7] that the failure mode was characterized by many horizontal cracks gradually developed within the range of 300 mm from the column base. A large horizontal crack occurred in the FRP-sheet at column base where drift of 5.5% was attained.
(≈74.25 mm displacement). Finally, not rupture of FRP sheet was noticed during loading until the end of the test.

4. NUMERICAL SIMULATION

OpenSees software is stable and suitable to simulate RC columns under monotonic or cyclic lateral load with constant axial load. This software has an important feature that allows implementing any new material into it. In this study, the nominated stress-strain models have been written in C++ language as Dynamic-Link-Library (DLL) file in OpenSees software (Version 2.4.6), which depends on the core files which contains all interfaces and abstract classes. In addition, one circular column has been modelled in OpenSees using Tool Command Language (TCL) with the following details. 1000-mm from column base was jacketed with FRP sheets and no gap was provide at the base, and this part of the column been divided into three elements; see Fig. 1.a. In addition, two elements represent the non-plastic hinge region, where these elements are established based on the displacement based beam-column element “dispBeamColumn” with 5- integration points for each element using fiber section method Figure 1.b&c to simulate the details of a cross section. For non-plastic region the concrete material has been represented by “Concrete01” for concrete cover, also this material has been selected to simulate the core section Figure 1.b, where the ultimate stress-strain values are calculated from reference [20]. For the column region confined with FRP sheet, the concrete material has been simulated with one of the previously mentioned models. The failure behaviour of RC column confined with FRP after FRP rupture was not defined in the existing axial stress-strain models. Therefore, in this study, the authors suggested definition of this stage based on that the stress will suddenly decrease at the ultimate stress to 0.2 $f_{cs}$ and the tangent is horizontal (i.e. tangent = 0); as shown in Figure 1.c.

The backbone curve of steel reinforcement as uniaxial material is represented by “ReinforcingSteel” [6] for longitudinal steel bars. For the same condition of comparison, it is noteworthy to clear that lateral steel confinement, buckling in longitudinal, tension in concrete, steel bars penetration (bond slips) have not been considered within the current simulation study. The boundary condition of this column is fixed at the column base and free to rotate and move at the top; see Figure 1.a.

The simulated column was subjected to cyclic lateral displacement with amplitudes matching well with the experimental values up to reach the ultimate displacement of the test column. Failure criteria was dependent on rupture of FRP sheets at the column-footing interface, and so the results of some cases would be continued further after the drift capacity defined experimentally for comparison with the other cases.

5. NUMERICAL RESULTS

The predicted axial stress-strain curves of FRP-confined concrete based on the nominated models as well as cyclic lateral load-displacement response of the simulated column are exhibited for each group in Figure 2, 3, & 4 for group (A), group (B) and group (C), respectively. The maximum lateral load and
the corresponding displacement, at which time FRPs attain rupture strain, have been exhibited in these Figures and also are listed in Table 22.

Figure 2 Predicted axial stress-strain curve and cyclic load-displacement for tested column (B2) for models in-group (A)

Figure 3 Predicted axial stress-strain curve and cyclic load-displacement for tested column (B2) for models in-group (B)

Figure 4 Predicted axial stress-strain curve and cyclic load-displacement for tested column (B2) for models in-group (C)

From Figure 2.a, 3.a, & 4.a, there are large differences among the axial stress-strain curves determined using the examined models, i.e. slope of the second branch and the values of the ultimate stress and strain. For instance, the ultimate strain $\varepsilon_{cc}$ has been ranged from 0.0047 to 0.0136 (mm/mm), and the ultimate stress $f_{cc}$ has minimum and maximum values of 27.06 MPa and 41.34 MPa, respectively. The minimum value is defined by the model of Hosotani and Kawashima (1999) [12] and it is lower than the concrete compressive strength of the unconfined concrete: strain softening response as shown.

(33.35, 0.0048)
in Figure 3.a. Those differences are dependent on the definition of the ultimate stress and strain given by the authors of the examined models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$P_f$ (kN)</th>
<th>$\delta_f$ (mm)</th>
<th>$P_f$(Theo.)</th>
<th>$\delta_f$(Theo.)</th>
<th>Model</th>
<th>$P_f$ (kN)</th>
<th>$\delta_f$ (mm)</th>
<th>$P_f$(Theo.)</th>
<th>$\delta_f$(Theo.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[11]</td>
<td>135.60</td>
<td>87.5</td>
<td>1.063</td>
<td>2.112</td>
<td>[13]</td>
<td>123.07</td>
<td>34.3</td>
<td>0.965</td>
<td>0.828</td>
</tr>
<tr>
<td>[12]</td>
<td>122.18</td>
<td>33.00</td>
<td>0.958</td>
<td>0.797</td>
<td>[16]</td>
<td>125.24</td>
<td>38.8</td>
<td>0.982</td>
<td>0.937</td>
</tr>
<tr>
<td>[10]</td>
<td>123.30</td>
<td>27.55</td>
<td>0.967</td>
<td>0.665</td>
<td>[19]</td>
<td>121.85</td>
<td>28.5</td>
<td>0.955</td>
<td>0.688</td>
</tr>
<tr>
<td>[14]</td>
<td>125.46</td>
<td>39.75</td>
<td>0.984</td>
<td>0.960</td>
<td>[17, 18]</td>
<td>123.61</td>
<td>32.8</td>
<td>0.969</td>
<td>0.792</td>
</tr>
<tr>
<td>[15]</td>
<td>121.34</td>
<td>20</td>
<td>0.951</td>
<td>0.483</td>
<td>[5]</td>
<td>120.86</td>
<td>29.61</td>
<td>0.948</td>
<td>0.715</td>
</tr>
</tbody>
</table>

$P_f$ is the maximum predicted lateral load at FRP rupture and $\delta_f$ is the corresponding displacement, $P_f$(Expr.) is the experimentally defined column maximum strength (127.5 kN) and the corresponding displacement is $\delta_f$(Expr.) = 41.42 mm.

For column cyclic response, Figure 2.b shows gradual increase in the lateral strength of the FRP-confined column after yielding of the main longitudinal reinforcement, however, the ultimate drift capacity (failure point, due to rupture of FRP sheet) is dependent on the definition of the values of the concrete ultimate compressive stress and the ultimate strain. For example, in Fig. 2.b, adoption of Samaan et al. stress-strain model [11] would overestimate the column maximum lateral load strength by almost 6% and also the corresponding displacement could be overestimated by around 210%. On the other hand, ultimate strain in Chastre and Silva [15] model is based on the size effect which in turn leads to a smaller values for the ultimate strain and stress compared to those of Samaan et al. model [11]. As a result, Fig. 2.b shows early termination of the column drift capacity corresponding to the maximum lateral strength. That is, the size effect parameter in this model still in need for further verification.

Using the stress-strain models of group B, Figure 3.b presents simulation results of the column B2. The column lateral displacement at FRP rupture is arranged and cleared by bullets according to the ultimate stress-strain values of each model studied [12, 10, 13, 16, and 19]. Apparent from this Figure, the main difference among the predicted hysteretic responses is the definition of the column ultimate displacement corresponding to FRP rupture. The least ultimate strain value of FRP-confined concrete in this group was defined by the model of ACI440.2-08 [10], and so column maximum lateral strength would be corresponding to a somewhat lower displacement of 27.55 mm. Although, Model [12] predicts a strain softening behaviour for FRP-confined concrete of the examined column, however the ultimate strain is comparable to that of the model [13] which almost shows elastic-perfectly plastic behaviour. This difference in the stress-strain relationship could not greatly affect the definition of the column displacement at FRP rupture. Here, the authors attribute this result to the difference in the definition of the transition point of both models, as the axial strain at transition point of the model proposed by [12] was greater than the counterpart defined by [13]. A clear effect for the definition of the FRP-confined concrete ultimate axial strength could be realized from the predicted responses of the examined column using the stress-strain relationships of the models [13 & 16]. Both models have the same definition for the first branch but Fahmy and Wu model [16] showed hardening performance for the confined concrete and thus the column could show a higher deformability. This value of ultimate displacement based on model [16] was the greatest among the predicted values using the other models.

In-group (c), the stress-strain relationships shown in Figure 4.a have unsmooth transition point between the first and second branches of the stress-strain relationship. Actually, when behaviour of FRP-confined concrete was represented by the models [5, 14, and 17& 18] to simulate the column cyclic response, several trails (such as change in the increment displacement) were required to prevent non-convergence problem at the transition point. From Figure 4.b, actual response of B2 column could not be exactly represented by any of the studied models. Although, Lim and Ozbakkaloglu model [5] was developed based on a large database of FRP-confined concrete, it showed early termination for column
lateral response at 29.61mm due to expected rupture of FRP at column-footing interface. In addition, although Rousakis et al [17, 18] models were developed for FRP-tube, it also failed to define the actual response of B2 column as rupture of FRP could take place at a lateral displacement of 32.8 mm.

Figure 5 displays the difference among two different types of the examined models [14 and 16] that have been established based on different mathematical equation. These models predicted, to some extent, identical stress-strain curves of FRP-confined concrete; see Figure 5.a. Figure 5.b indicates that there is no clear difference among the column lateral load-displacement responses using both models. In other words, the parabolic curve in the second branch in Harajili model [14] compared to linear curve in the other model has no significant effect on lateral load-displacement. Therefore, selection the simplest model for predicting the axial stress-strain curve is a practical choice.

Generally, the examined models [5, 10, 13, 15 and 17&18] have been established based on reduction factor for ultimate hoop strain, which affects the definition of both ultimate axial stress and the corresponding strain and in turn early termination of column deformability due to early rupture of FRP. In the light of a wider database of FRP-jacketed columns, it would be better to examine the possibility of omitting this factor in case of column subjected to combined effect of axial and lateral loads.

![Figure 5 Comparison among the different type of models in cyclic response](image)

Ultimately, except Samaan et al. model [11], no one of the other examined models can accurately predicts the column ultimate displacement compared to the experimental value due to the early predicted rupture of FRP sheets at column-footing interface, which was not the real case of the experimentally tested column as previously discussed. Therefore, there is an urgent need for future study defining an appropriate stress-strain model of FRP-confined concrete that can be applied for accurate simulation of column response to the effect of lateral loading.

6. CONCLUSIONS

The following conclusion can be drawn based on simulation results:
1) Although, most of the selected models could reasonably predict the lateral strength of the simulated column, most of them showed different estimation for the corresponding lateral drift capacity.
2) Nine of the examined models failed to exactly predict the failure mode of the test column, and only Samaan et al. model [11] showed a very late rupture of FRP sheets at a lateral displacement beyond the experimental column drift capacity.
3) Future works should focus on the hysteretic response of a wide data-base of FRP-RC columns to define the most reliable stress-strain model for numerical simulation.

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