DESIGN ORIENTED APPROACHES FOR FRP RETROFITTED RC COLUMNS
AND CASE STUDY OF TEC2007 EXAMPLE

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ABSTRACT

Enhancing ductility and shear capacity of rectangular RC columns by means of FRPs has been accepted as a beneficial retrofitting technique and the implementation of the fiber based materials has been permitted in structural retrofitting codes since the last decades. Herein, regarding the retrofitting design guidelines; the seismic performance of flexure dominated RC columns has been evaluated by overseeing safety regulations. Thus, taking the Turkish Earthquake Code (TEC2007) in concern as a pilot study, this research focuses on the assessment of FRP strengthened RC columns accordingly and asserts new simple design equations based on inter-story drifts and ultimate compressive strains for FRP strengthened RC columns. For both of the design methods, the ratios of FRP confinement, axial load and longitudinal reinforcement were utilized since these parameters were observed to be the most emphatic ones according to the generated column database including 28 FRP strengthened RC columns. The obtained results revealed that the design equations for inter-story and ultimate compressive strain based approaches came up with close results with each other. Moreover, the ultimate concrete strain based approach provided more realistic results than inter-story drift based approach since standard section analysis was employed with plastic hinge model in order to calculate ultimate drift levels for FRP confined columns. In advance, both of the approaches can be adapted to similar FRP retrofitting guidelines to respond to the needs of engineers for easier and quicker FRP strengthened column design methods.

KEYWORDS

FRPs, rectangular RC columns, strengthening, flexural behaviour, design, Turkish Earthquake Code

INTRODUCTION

The practicality and efficacy of FRP wrapping in strengthening RC columns under simulated earthquake loads was firstly demonstrated by the keystone researches in 1990’s (Seible et al. 1995; Saadatmanesh et al. 1997). This trend in FRP research conduced engineers to implement FRP strengthening in structural regulations such as ACI440 and Eurocode8. Very similar to the regulations of ACI440, the Turkish Earthquake Code (TEC2007) FRP strengthening equations are based on ultimate stress and strain values of FRP confined concrete. The formulations are also similar in terms of confinement effectiveness factor and lateral confining pressure while simpler formulations exist for design purposes in TEC2007. Since both of the codes propose only one design parameter of lateral FRP confining pressure, this research points out the most prominent parameters including the ratios of lateral confinement, axial load and longitudinal reinforcement. In order to inspect the TEC2007 design guidelines, the results of an experimental study with four FRP strengthened columns were used. In addition, a database of 28 FRP strengthened columns was generated on account of asserting new design formulations for FRP strengthening of RC columns.

EXPERIMENTAL COMPARISON

In order to compare the TEC2007 design method with the experimental results, four square moderate strength RC columns were used (Ozcan et al., 2008). The tests were conducted in Structural Mechanics Laboratory of Middle East Technical University and the RC columns were wrapped either with one or two wraps of CFRP. The TEC2007 requirements are summarized as follows in Equations 1a to c. According to the code, a bilinear stress-strain relationship for FRP confined concrete is considered. For the model, first point refers to the strain value of 0.002 and concrete compressive strength whereas the second point is found by locating the ultimate strain value...
and corresponding stress value as stated in Equation 1a. The obtained results of ultimate drift levels ($DR_u$) from the experiments including four CFRP wrapped RC columns are shown in Table 1. Following the design requirement in TEC2007, the yield values of curvatures and moments are obtained in addition to the ultimate values. In order to obtain column tip deflections regarding the curvature distribution over the column height, plastic hinging model was used as shown in Equation 2.

$$f_{cc} = f_c \left(1 + \frac{f_t}{f_c'}\right) \geq 1.2 f_{cmr} \epsilon_{cc} = 0.002 \left(1 + 15 \left(\frac{f_t}{f_c'}\right)^{0.75}\right)$$  \hspace{1cm} (1a)

$$\phi = \frac{f_t}{f_c'} = \frac{(b + h) E_f \epsilon_f}{bh f_c'} \kappa_a, \epsilon_f \leq 0.004$$  \hspace{1cm} (1b)

$$\kappa_a = \frac{1}{3bh} \left(\frac{h - 2r}{2}\right)^2 + \left(\frac{h - 2r}{2}\right)^2$$  \hspace{1cm} (1c)

$$\Delta_u = \Delta_y + \Delta_p = \frac{\kappa_a L_p^2}{3} + \left(\kappa_a - \kappa_y\right) L_p \left(\frac{L - L_p}{2}\right), \ L_p = \frac{h}{2}$$  \hspace{1cm} (2)

In which, $f_{cc}, \epsilon_{cc}, f_c', f_t$ denote FRP confined concrete stress and strain, unconfined concrete strength and lateral confinement pressure, respectively. $\phi, b, h, r, E_f, \epsilon_f, \epsilon_u, \epsilon_{fu}$ and $\kappa_a$ refer confinement ratio, column width, depth, corner rounding radius, FRP elasticity modulus, FRP strain, FRP ultimate strain, FRP jacket thickness and confinement effectiveness factor, respectively. In Equation 2, $\Delta_u, \Delta_y$ and $\Delta_p$ indicate yield, plastic and ultimate column tip deflection. $L_p$ is the assumed plastic hinge length of the column. For the calculation of the yield curvatures, the yield moments are divided into cracked stiffness values that were evaluated considering the axial load level on the column. The uncracked stiffness values are reduced according to the axial loads by interpolating the reducing factor between 0.4 and 0.8 with respect to the axial load levels from 10 to 40% of capacity, respectively. Table 2 summarizes the analytically acquired yield and ultimate deflection values calculated according to TEC2007.

### Table 1. Test specimen details and obtained results

<table>
<thead>
<tr>
<th>b (mm)</th>
<th>h (mm)</th>
<th>L (mm)</th>
<th>r (mm)</th>
<th>$f_c'$ (MPa)</th>
<th>$A_s$ (mm²)</th>
<th>$\kappa_a$</th>
<th>$\rho$ %</th>
<th>$n^*$ %</th>
<th>$\phi$ %</th>
<th>$DR_u$</th>
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<tbody>
<tr>
<td>S-L-1-00</td>
<td>350</td>
<td>350</td>
<td>2000</td>
<td>30</td>
<td>19.4</td>
<td>2035.8</td>
<td>0.542</td>
<td>1.66</td>
<td>27</td>
<td>0.091</td>
</tr>
<tr>
<td>S-L-1-34</td>
<td>350</td>
<td>350</td>
<td>2000</td>
<td>30</td>
<td>14.0</td>
<td>2035.8</td>
<td>0.542</td>
<td>1.66</td>
<td>34</td>
<td>0.126</td>
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<tr>
<td>S-L-2-00</td>
<td>350</td>
<td>350</td>
<td>2000</td>
<td>30</td>
<td>11.4</td>
<td>2035.8</td>
<td>0.542</td>
<td>1.66</td>
<td>40</td>
<td>0.309</td>
</tr>
<tr>
<td>S-L-2-32</td>
<td>350</td>
<td>350</td>
<td>2000</td>
<td>30</td>
<td>15.6</td>
<td>2035.8</td>
<td>0.542</td>
<td>1.66</td>
<td>32</td>
<td>0.226</td>
</tr>
</tbody>
</table>

* $N = 0.85 f_c' bh + A_s f_{sy}$

### Table 2. Analytically obtained results using TEC2007

<table>
<thead>
<tr>
<th>$\kappa_y$ (rad/km)</th>
<th>$M_y$ (kNm)</th>
<th>$M/EI_{cr}$ (rad/km)</th>
<th>$\kappa_a$ (rad/km)</th>
<th>$M_u$ (kNm)</th>
<th>$\Delta_u$ (mm)</th>
<th>$F_y$ (kN)</th>
<th>$\Delta_p$ (mm)</th>
<th>$F_u$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-L-1-00</td>
<td>9.79</td>
<td>124.61</td>
<td>7.24</td>
<td>24.65</td>
<td>140.94</td>
<td>9.65</td>
<td>62.31</td>
<td>15.48</td>
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<tr>
<td>S-L-1-34</td>
<td>11.59</td>
<td>116.10</td>
<td>6.86</td>
<td>23.38</td>
<td>122.62</td>
<td>9.14</td>
<td>58.05</td>
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<tr>
<td>S-L-2-00</td>
<td>13.07</td>
<td>110.26</td>
<td>6.58</td>
<td>34.82</td>
<td>115.74</td>
<td>8.77</td>
<td>55.13</td>
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<tr>
<td>S-L-2-32</td>
<td>10.83</td>
<td>120.22</td>
<td>7.06</td>
<td>34.22</td>
<td>133.24</td>
<td>9.42</td>
<td>60.11</td>
<td>18.51</td>
</tr>
</tbody>
</table>

Considering the aforementioned design guidelines according to TEC2007, the obtained results are shown in Figure 1a-d. As can be observed from the Figures 1a-d, the TEC2007 predictions underestimate the column performances observed during the tests in terms of attainable ultimate drift ratios and lead to a consequent over safe FRP strengthening design. Since the additional deflection constituents of fixed-end and shear were not added and only the flexural components were in consideration, the observed ultimate drift levels for the column tests were underestimated. Thus, two design methods were generated by augmenting the test database by adding 24 new FRP strengthened columns that were the results of previous studies (Bousias et al., 2004; Iacobucci et al., 2003; Sause et al., 2004; Memon et al., 2002 and Ozcan et al., 2008).
PROPOSED DESIGN METHODS

Method 1: Inter-story Drift Based Approach

The first approach in FRP design of RC columns is based on ultimate drift levels at which the column lateral resistance dropped 80% of its lateral capacity. For all the columns, the confinement ratios were calculated by using Equations 1b and c. Then, the ultimate drift ratios were estimated by using nonlinear regression analysis with the parameters of confinement, axial load and longitudinal reinforcement ratios. By using this simple analysis procedure, an exponential expression was obtained as shown in Equation 3. This equation was simplified that represents the lower limit for the exponential equation. Figures 2a and b shows the comparisons of experimental and predicted drift values for best-fit and design solutions. All the parameters of $\phi$, $n$ and $\rho$ are in %. The design results of the tests for Method 1 are shown in Figures 1a-d.

$$DR_u = 2.47 + 50 \frac{\phi^{0.64}}{n^{-0.29} \rho^{0.35} \cdot 2 + 4.5 \phi n \rho}$$  \hspace{1cm} (3)
Method 2: Ultimate Concrete Strain Based Approach

For the second method proposed, the ultimate concrete strains were estimated while using concrete stress block and elastoplastic steel behaviour assumptions for standard section analysis. During the calculations, the yield deflections are calculated and subtracted from the experimental ultimate tip deflections in order to find ultimate curvature values by equating the plastic hinge length to the height of the section as shown in Equation 2. Subsequently, the required ultimate compressive strains for concrete were evaluated and the same nonlinear regression procedure was implemented as Method 1 by employing the ratios of confinement, axial load and longitudinal reinforcement. The acquired exponential equation is shown in Equation 4 and its lower limit that provides safer design provision is also stated. The comparison graphs with the test database are shown in Figures 3a and b. Herein, the parameters of $n$ and $\rho$ are in % while $\phi$ has no units. By using the design strains for the tested columns, the obtained results for Model 2 are presented in Figure1a-d.

$$\varepsilon_{cc} = 0.019 + 0.418 \frac{\phi}{n \rho} \rightarrow \varepsilon_{cc} = 0.015 + 2.3 \frac{\phi}{n \rho}$$

(4)

Figure 3 Experimental comparisons with predicted (a) bestfit and (b) Design Equations of concrete strains

RESULTS AND CONCLUSIONS

The evaluation of TEC2007 was made and the significant underestimation of drift ratios were observed throughout the testing program having four FRP strengthened columns. In comparison with the code, two new design approaches that were based on inter-story drift and ultimate concrete strain were proposed. According to the test result comparisons, Method 1 came up with higher deflection levels than Method 2. Since Method 2 takes more parameters into account, such as plastic hinge length and section analysis, it can be mentioned that Method 2 can be used for more detailed analysis by giving more accurate results than Method 1. Thus, Method 1 should be used for quicker and simpler analysis. In addition, both of the methods can be implemented to the other FRP related codes with a suitable database in order to observe the employed parameters.

REFERENCES


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