Simulation of Eccentrically Loaded Rectangular Reinforced Concrete Columns Confined with FRP Composites

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Abstract: This study presents the results of nonlinear finite element (FE) analysis of GFRP-confined rectangular reinforced concrete (RC) columns under eccentric loads. The test variables are the number of GFRP layers and intensity of load eccentricity. It was found that the general trends of the FE analysis results agreed favorably with the results of the experimental studies reported in the literature. The FE analysis results showed that GFRP wrapping of RC columns has significantly increased their load carrying capacity and ductility. The results also indicate that the presence of eccentricity of loading reduces the load carrying capacity and performance of the strengthened RC columns.

Keywords: Eccentric load, FE Analysis, FRP wrapping, and Reinforced Concrete Columns.

1. Introduction

The retrofitting of reinforced concrete structures has become necessary in recent years due to one or combination of many factors such as alteration in usage, construction errors and deterioration due to a natural disaster or aggressive environmental conditions. Fiber reinforced polymer (FRP) composites has been used in recent decades for strengthening and rehabilitation of damaged concrete structures (such as beams, columns and slabs) to improve structural integrity. The Potential characteristics of the FRP composites such as high strength, corrosion resistance and lightweight make it the most suitable jacketing material over the convention steel jacketing. Several experimental studies have been conducted in recent years on the behavior reinforced concrete columns confined with FRP composites and have proven to be effective in enhancing the structural performance of the columns [1-5]. Most of these studies focus on concentrically loaded RC columns with circular sections. However, limited studies investigate the behavior of eccentrically loaded non-circular RC columns confined with FRP reinforcements. Moreover, it is apparent that in an ideal situation, most of the columns in buildings are non-circular section subjected to both axial compression and bending action [6, 7]. Chaallal and Shahawy [8] have investigated the performance of rectangular RC columns wrapped with bidirectional CFRP under combined axial and flexural loading. The results of their investigation showed that the combined action of longitudinal and transverse weaves of the bidirectional CFRP fabric has significantly improved the load carrying capacity of the strengthened columns. The influence of strain gradient in small-scale eccentrically loaded CFRP confined square concrete columns was investigated by Azadeh and Wei [9] They found that CFRP wrapping of the columns could enhance the strength and ductility of the strengthened columns under eccentric loading. They also observed that axial strain gradient resulting from the presence of load eccentricity could limit the CFRP strengthening capacity to about 20%. Hadi and Widiarsa [10] have investigated the influence of CFRP wrapping on the behavior of square RC columns under varying eccentric loadings. The results have indicated that CFRP wraps could significantly improve the strength and ductility of the strengthened RC columns. The results also showed a decreasing load carrying capacity of the strengthened columns with increasing load eccentricity. Daugevičius, et al. [11] studied the influence of load eccentricity on CFRP-confined rectangular RC columns. The results of their findings indicated that the ultimate capacity of the strengthened columns decreases to about 64% with increasing load eccentricity.

Finite element method (FEM) of analysis is one of the numerical techniques for achieving an approximate solution of ordinary and partial differential equations of a system by discretization process. It
is a very compelling computational tool proved by numerous engineering applications and research. Mimiran et al. [12] used a nonlinear finite element method to simulate the cyclic response of circular and square concrete columns confined by FRP composites using ANSYS software. They used a non-associative Drucker-Prager plasticity model to account for the pressure responsiveness of concrete. Their predicted stress-strain results correlated positively with their experimental results. Their FE analysis results also revealed a stress concentration around the corners of the square concrete section, as seen in their experimental study. Feng et al. [13] used William Warnke [14] model with five parameters in their FE analysis to model axially loaded FRP confined square concrete columns. They used FE program ANSYS to simulate the performance of the columns. The authors confirmed that FE analysis could efficiently simulate the behavior of FRP confined concrete columns when a proper numerical model is applied. In this study, a nonlinear finite element method is used to study the impact of some test parameters on the performance of rectangular RC columns wrapped with FRP reinforcement under eccentric load. These test parameters include the number of FRP layers, load eccentricity and compressive load carrying capacity.

2. Finite Element Modeling

This study develops a nonlinear finite element model for FRP confined rectangular RC columns under eccentric loads. A series of rectangular RC columns were wrapped with 1, 2 and 3 layers of a unidirectional GFRP sheets. All the RC columns have a uniform grade of concrete $f_{cm}=30$MPa. The clear concrete cover of 20mm was used. Summarized in Table 1, are the details of the column specimens. All the column specimens were simulated in ANSYS workbench (Products 18.1). ANSYS is a compelling program in engineering simulation that can execute simple static analysis as well as complex nonlinear dynamic analysis.

<table>
<thead>
<tr>
<th>Test Specimens</th>
<th>Internal Reinforcement</th>
<th>Test Eccentricity</th>
<th>No of GFRP Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0LW-0e</td>
<td>4-Y12mm and R6mm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1LW-0e</td>
<td>4-Y12mm and R6mm</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2LW-0e</td>
<td>4-Y12mm and R6mm</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3LW-0e</td>
<td>4-Y12mm and R6mm</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>0LW-25e</td>
<td>4-Y12mm and R6mm</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>1LW-25e</td>
<td>4-Y12mm and R6mm</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>2LW-25e</td>
<td>4-Y12mm and R6mm</td>
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<td>2</td>
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<td>3LW-25e</td>
<td>4-Y12mm and R6mm</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>0LW-50e</td>
<td>4-Y12mm and R6mm</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>1LW-50e</td>
<td>4-Y12mm and R6mm</td>
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<td>1</td>
</tr>
<tr>
<td>2LW-50e</td>
<td>4-Y12mm and R6mm</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>3LW-50e</td>
<td>4-Y12mm and R6mm</td>
<td>50</td>
<td>3</td>
</tr>
</tbody>
</table>

Source: The Author

2.1. Element Types and Material Models

2.1.1. Reinforced Concrete

A reinforced concrete solid element SOLID65 was used to model concrete. The element is capable of cracking in tension, crushing in compression and resisting plastic deformations. The element is defined by 8-nodes having three degrees of freedom at each node. The geometry, node positions and the coordinate systems for a SOLID65 element are depicted in Fig 1. In modern fracture mechanics, concrete is recognized as a quasi-brittle material, and its behavior under loading is entirely different in compression and tension [15]. The material properties required for concrete in ANSYS includes elastic modulus ($E_c$), ultimate uniaxial compressive strength ($f_{cm}$), ultimate uniaxial tensile strength (modulus of rupture $f_t$), Poisson’s ratio ($\nu$), shear transfer coefficient ($\beta_4$) and uniaxial stress-strain relationship for concrete in compression. The elastic modulus and tensile strength (modulus of fracture) of concrete are calculated using equations (1) and (2) below [16]:

$$E_c = 4700\sqrt{f_{cm}}$$  \hspace{1cm} (1)

$$f_c = 0.7\sqrt{f_{cm}^2}$$  \hspace{1cm} (2)
The Poisson’s ratio of concrete was assumed to be 0.2 for all the specimens. The shear transfer coefficient used in the present study is 0.2 for a smooth crack and 0.8 for a rough crack. The stress-strain curve for concrete is constructed using the numerical expressions proposed by Desayi and Krishnan [17], (equations 3 and 4) along with expressions developed by Grere [18] (Equation 5).

\[ f = \frac{E_c \varepsilon}{1 + (\varepsilon / \varepsilon_0)^2} \]  

(3)

\[ \varepsilon_0 = \frac{2f'_{c}}{E_c} \]  

(4)

\[ E_c = \frac{f}{\varepsilon} \]  

(5)

Where: \( f \) is stress at any given strain \( \varepsilon \) and \( \varepsilon_0 \) is the strain corresponding to ultimate compressive strength \( f'_{c} \).

**2.1.2. Steel Reinforcement**

Steel reinforcement was modeled with a 3-D spar LINK180 element, which is a uniaxial tension-compression element having three translational degrees of freedom at each node. The geometry, node positions and coordinate systems for LINK180 element are shown in Fig 2. For finite element models, steel reinforcement is assumed to be elastic-perfectly plastic material and identical in tension and compression [20, 21]. The steel reinforcement employed in this investigation consists of a 12mm diameter longitudinal bar and 6mm diameter bar as hoop ties with nominal properties \( E_s=200000\text{MPa} \), \( f_y=460\text{MPa} \) and \( \nu=0.3 \).
2.1.3. FRP Composites

A four-node shell element (SHELL181) with six degrees of freedom at each node was used to model FRP composites. The element is suitable for analyzing thin to moderately thick shell structures. This element is well adapted for linear, large rotation, and considerable strain nonlinear applications. The geometry, node positions and the element coordinate systems for a SHELL181 element are illustrated in Fig 3. The input material properties of GFRP composites used in the present study are presented in Table 2 below.

![Fig 3. SHELL181 geometry and coordinate system](image)

Table 2. Summary of material properties of GFRP composites

<table>
<thead>
<tr>
<th>Elastic Modulus (MPa)</th>
<th>Major Poisson’s ratio</th>
<th>Tensile Strength (MPa)</th>
<th>Shear Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x = 21,000$</td>
<td>$v_{xy} = 0.26$</td>
<td>600</td>
<td>$G_{xy} = 1520$</td>
</tr>
<tr>
<td>$E_y = 7,000$</td>
<td>$v_{yz} = 0.26$</td>
<td></td>
<td>$G_{yz} = 1520$</td>
</tr>
<tr>
<td>$E_z = 7000$</td>
<td>$v_{xz} = 0.3$</td>
<td></td>
<td>$G_{xz} = 2650$</td>
</tr>
</tbody>
</table>

Source: Kachlakev, et al. [21].

2.1.4. End Corbel

The primary purpose of the end corbel is to transfer the load to the column in the test region. In this model, the end corbel was model as a single mass element. However, the stiffness behavior of the end corbels was characterised as rigid to prevent deformation of the corbels throughout the solution process.

2.2. Modeling and Meshing

The geometry of a full-size FRP strengthened rectangular RC column with end corbels was created in the ANSYS workbench design modeler. A rectangular solid with end corbels was first created with specified dimensions and corner radius. A hollow rectangular surface body with a specified thickness and corner radius was also created. A corner radius of 20mm was maintained for all the specimens. The interior steel reinforcements were also created as line bodies within the rectangular solid. In this model, the rectangular solid represents the concrete and the hollow rectangular surface body acts as the bonded FRP composites. Mapped meshing was used to mesh the generated model as it helps in controlling the number of elements/nodes. Mesh size of 20mm is used in this model. The adjacent mesh nodes of concrete and steel reinforcement were connected using the node merge tool. Figs 4 and 5 illustrate the finite element model of eccentrically loaded GFRP wrapped rectangular RC columns.

2.2.1. Boundary Conditions and Load Application

In this model, the y-axis of the coordinate system corresponds to the axis of the rectangular RC column. The following boundary conditions were applied:
a. The bottom surface of the column was sliced according to the position of the fixed support. All the coupled nodes on the bottom surface are restrained from all degrees of freedom in three directions.

b. The top surface of the column was also sliced according to the position of the applied eccentric load. The load was applied incrementally normal to the axis of the column.

**Fig 4.** Finite element mesh for GFRP confined rectangular RC column

![Finite element mesh for GFRP confined rectangular RC column](source: The Author)

**Fig 5.** Concrete, Steel and GFRP elements in the full model rectangular column

![Concrete, Steel and GFRP elements in the full model rectangular column](source: The Author)

### 2.2.2. Simulation

ANSYS program employs the Newton-Raphson method in solving problems that involved nonlinear structural behavior. In the present nonlinear analysis, automatic load stepping feature was activated as it enables the solver to predict and controls the number of load steps. However, the automatic time stepping was defined in terms of sub-steps to enable loads to be applied gradually. The number of sub-steps used varied from 20 to 200 with the minimum sub-step set to $1/200^{th}$ of the applied load. Large deflection feature in solver controls was also activated.
3. Finite Element Analysis Results and Discussions

3.1. Behavior of the Simulated Columns

A nonlinear FE analysis was carried out on rectangular RC columns confined with GFRP wraps under eccentric loads. The entire wrapped RC columns exhibit limited deformation. The results of FE analysis are summarised in Table 3. Fig 6 depicts the deformation behavior of the strengthened rectangular RC columns. The stress distribution over the section of the strengthened RC columns at varying load eccentricities is also portrayed in Fig 7 and Fig 9. It is apparent from Fig 7 that the concrete stress distribution for concentrically loaded columns is higher at the corners than at the edges and middle of the column section. This confirmed that the corner radius of the column section could significantly influence the efficiency of the external FRP reinforcement. From Fig 8 and Fig 9, it is also clear that the concrete stress distributions for the strengthened columns under eccentric load is maximum in the compression area and drop gradually to a minimum in the tension area. The performance of the simulated columns was analyzed using their ductility. The ductility of the columns was determined as the ratio of the axial displacement at ultimate load to the axial displacement at yield load. The results in Table 3 indicate a positive increase in the ductility of the strengthened columns with an increase in the number of GFRP layers.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Eccentricity (mm)</th>
<th>Ultimate load (KN)</th>
<th>Displacement at ultimate load (mm)</th>
<th>Yield load (KN)</th>
<th>Displacement at yield load (mm)</th>
<th>Ductility index</th>
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</thead>
<tbody>
<tr>
<td>0LW-0e</td>
<td>0</td>
<td>234</td>
<td>0.37</td>
<td>227</td>
<td>0.25</td>
<td>1.48</td>
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<tr>
<td>1LW-0e</td>
<td>0</td>
<td>315</td>
<td>0.57</td>
<td>303</td>
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<tr>
<td>2LW-0e</td>
<td>0</td>
<td>342</td>
<td>0.59</td>
<td>306</td>
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<tr>
<td>3LW-0e</td>
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<td>360</td>
<td>0.67</td>
<td>342</td>
<td>0.36</td>
<td>1.86</td>
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<tr>
<td>0LW-25e</td>
<td>25</td>
<td>160</td>
<td>1.62</td>
<td>143</td>
<td>1.06</td>
<td>1.53</td>
</tr>
<tr>
<td>1LW-25e</td>
<td>25</td>
<td>180</td>
<td>2.40</td>
<td>160</td>
<td>1.30</td>
<td>1.85</td>
</tr>
<tr>
<td>2LW-25e</td>
<td>25</td>
<td>205</td>
<td>1.52</td>
<td>183</td>
<td>1.08</td>
<td>1.41</td>
</tr>
<tr>
<td>3LW-25e</td>
<td>25</td>
<td>231</td>
<td>2.36</td>
<td>212</td>
<td>1.41</td>
<td>1.67</td>
</tr>
<tr>
<td>0LW-50e</td>
<td>50</td>
<td>125</td>
<td>1.99</td>
<td>118</td>
<td>1.37</td>
<td>1.45</td>
</tr>
<tr>
<td>1LW-50e</td>
<td>50</td>
<td>158</td>
<td>1.65</td>
<td>135</td>
<td>1.11</td>
<td>1.49</td>
</tr>
<tr>
<td>2LW-50e</td>
<td>50</td>
<td>170</td>
<td>1.95</td>
<td>163</td>
<td>1.34</td>
<td>1.46</td>
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<tr>
<td>3LW-50e</td>
<td>50</td>
<td>190</td>
<td>2.96</td>
<td>175</td>
<td>1.74</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Table 3. Summary of FE analysis results for the simulated columns

Source: The Author

Fig 6. Deformation behaviour of GFRP wrapped columns under (a) concentric loading (b) Eccentric loading

Source: The Author
The load-displacement curves for concentrically loaded GFRP wrapped columns are shown in Fig 10. It can be seen clearly that the columns experienced similar stiffness trends before failure. It is also evident from the Figure that wrapping the RC columns with GFRP composites improved the performance of the columns by increasing their displacement at failure. The highest load carrying capacity was realized by column 3LW-0e with 54% enhancement compared to the unwrapped column (0LW-0e).
3.2 Effect of eccentricity of loading

The influence of eccentricity of loading on the performance of the strengthened columns is assessed by plotting the load-displacement curve for the columns under various load eccentricities based on their number of GFRP wraps. Fig 11 and Fig 14 depict the load-displacement curves for GFRP strengthened RC columns under different load eccentricities. It is evident from the Figures that the presence of load eccentricity results in the decrease in the performance of the RC columns.
The variation of ultimate load carrying capacity with eccentricity for the RC columns wrapped with varying number of GFRP layers is portrayed in Fig 15. It is clear that the overall performance of the columns is improved with an increase in the number of GFRP wraps. It is also evident that presence of eccentricity of loading has resulted in the decrease in performance of the strengthened columns.
4. Conclusion

A 3D finite element analysis of eccentrically loaded rectangular RC columns wrapped with GFRP composites is presented in this study. The variables that influenced the behavior of the columns include the number of FRP layers and eccentricity of loading. The general trends of the FE analysis results agreed favorably with the results of the experimental studies reported in the literature. Based on the finite element simulation results obtained in this study, the following conclusions can be drawn;

- The GFRP wrapped RC columns have demonstrated excellent performance with regard to load carrying capacity and ductility. The highest performance is achieved by columns wrapped with 3 layers of GFRP.
- It was revealed that the eccentricity of loading have resulted in a decrease in the load carrying capacity and performance of the strengthened RC columns.

5. References


