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Finite element analysis of rectangular reinforced concrete columns wrapped with FRP composites

Abdurra'uf M Gora[1*], Jayaprakash Jaganathan[2], M P Anwar[3], U Johnson Alengaram[4]
[123] Department of Civil Engineering, University of Nottingham Malaysia
[4] Faculty of Engineering, Department of Civil Engineering, University of Malaya, Kuala Lumpur, Malaysia
[*]Email: keex5aur@nottingham.edu.my/amgora.civ@buk.edu.ng

Abstract. Fibre reinforced polymer (FRP) wrapping of reinforced concrete (RC) columns has increasingly become the most suitable method used to strengthen and rehabilitate RC columns. It is clear that limited studies have investigated the behaviour of eccentrically loaded RC columns wrapped with FRP composites. In the present study, a three-dimensional finite element (FE) model was developed to simulate the behaviour of rectangular RC columns wrapped with glass fibre-reinforced polymer (GFRP) sheets under concentric and eccentric loading. The FE model was developed in the finite element analysis software ANSYS. The variables within the FE model are the number of GFRP layers and the magnitude of load eccentricity. The FE analysis results showed that GFRP wrapping significantly improved the performance of the strengthened columns by delaying concrete rupture. The presence of load eccentricity reduced the load carrying capacity and performance of the strengthened RC columns. The FE model correlated well with the stress distribution trends observed in the literature.

1. Introduction

Advanced fibre reinforced polymer (FRP) composites are becoming increasingly popular in the strengthening and rehabilitation of damaged civil engineering structures, such as beams, columns and slabs. FRP composites are used to improve load carrying capacity and structural integrity. A considerable number of experimental studies have been undertaken showing how effective FRP composites are in enhancing the structural performance of columns [1–5]. Most studies focused on concentrically loaded RC columns with circular sections. However, it is apparent that most columns are non-circular in section and are subjected to both axial compression and bending.

Finite element analysis (FEA) is a numerical method used to obtain an approximate solution of ordinary and partial differential equations through discretisation. It is a very powerful computational tool used in many engineering applications and research. Mimiran et al. [6] used a nonlinear finite element approach to simulate the cyclic response of circular and square concrete columns confined by FRP composites using ANSYS software. A non-associative Drucher-Prager plasticity model was used to account for the pressure sensitivity of concrete. The predicted stress-strain results correlated well with the test results. The FEA results also showed a stress concentration around the edges of the square concrete section, as observed in the experimental work. Feng et al. [7] used the William Warnke [8] model with five parameters in the FEA to represent the failure criterion of axially loaded FRP-confined square concrete columns. ANSYS was used to confirm that FEA can efficiently simulate the behaviour of FRP confined concrete columns when an appropriate numerical model is employed. The present work is aimed at contributing to the understanding of the behaviour of RC columns wrapped with FRP under

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concentric and eccentric loadings. The primary effort focused on the influence of the number of GFRP wraps and the magnitude of eccentricity of loading on the performance and load carrying capacity of rectangular RC columns wrapped with GFRP.

2. Finite Element Modelling

This study develops a nonlinear finite element model for FRP confined rectangular RC columns under eccentric loads. A series of 100 × 150 × 500mm rectangular RC columns were wrapped with one, two and three layers of unidirectional GFRP sheets. Figure 1 illustrates the reinforcement details of the column specimens. All the RC columns have a uniform grade of concrete f'_{co}= 30MPa. A clear concrete cover of 20mm was used. Table 1 summarizes the details of the test program and the specimen properties. All the column specimens were simulated in ANSYS workbench (Products 18.1) at the University of Nottingham Malaysia. ANSYS is well-established FE engineering simulation program that can execute simple static analysis as well as sophisticated nonlinear dynamic analysis. However, like all other finite element packages, the ANSYS program has its own nomenclature and analysis procedures that need to be specified before executing the analysis. In the present study, SOLID65, SHELL181, LIINK180 and MASS21 were used to model concrete, FRP, steel reinforcement and end corbels, respectively. The following subsections discuss the detailed formulation of the finite element model.

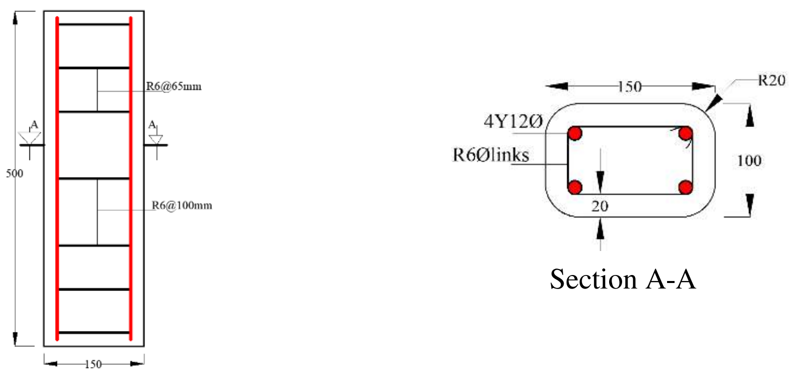

Figure 1. Details of column specimen

Table 1. Detail of the Column specimens

Test Specimens	FRP Wrapping condition	Internal Reinforcement	Test Eccentricity (mm)	No of GFRP Layers
UW-0ec	Unwrapped	4-Y12mm and R6mm	0	0
1W-0ec	Wrapped	4-Y12mm and R6mm	0	1
2W-0ec	Wrapped	4-Y12mm and R6mm	0	2
3W-0ec	Wrapped	4-Y12mm and R6mm	0	3
UW-15ec	Unwrapped	4-Y12mm and R6mm	15	0
1W-15ec	Wrapped	4-Y12mm and R6mm	15	1
2W-15ec	Wrapped	4-Y12mm and R6mm	15	2
3W-15ec	Wrapped	4-Y12mm and R6mm	15	3
UW-30ec	Unwrapped	4-Y12mm and R6mm	30	0
1W-30ec	Wrapped	4-Y12mm and R6mm	30	1
2W-30ec	Wrapped	4-Y12mm and R6mm	30	2
3W-30ec	Wrapped	4-Y12mm and R6mm	30	3

2.1. Material Properties

2.1.1. Concrete

The material properties required for a SOLID65 element in ANSYS include: elastic modulus (E_c), ultimate uniaxial compressive strength (f_{co}), ultimate uniaxial tensile strength (modulus of rupture f_t), Poisson's ratio (v), shear transfer coefficient (β_t) and the uniaxial stress-strain relationship for concrete in compression. The elastic modulus and tensile strength (modulus of rupture) of concrete are calculated using the equations below [9].

$$E_c = 4700\sqrt{f_c'} \tag{1}$$

$$f_t = 0.7\sqrt{f_c'} \tag{2}$$

Poisson's ratio for concrete was assumed to be 0.2 for all the specimens. The shear transfer coefficient is 0.2 for a smooth crack (complete loss of shear transfer) and 0.8 for a rough crack (no loss of shear transfer). The stress-strain curve for concrete is constructed using the numerical expressions proposed by Desayi and Krishnan [10] (equations 3 and 4) together with expressions developed by Grere JM [11] (equation 5). The uniaxial stress-strain relationship for concrete in compression is presented in Table 2 and illustrated in Figure 2.

$$f = \frac{E_c \varepsilon}{1+\left(\varepsilon/\varepsilon_o\right)^2} \tag{3}$$

$$\varepsilon_o = {2f_c'}/{E_c} \tag{4}$$

$$E_c = {f}/{\varepsilon} \tag{5}$$

where f is stress at any given strain ε and ε_o is the strain corresponding to the ultimate compressive strength f_c'.

Table 2. Summary of stress-strain results for concrete 30MPa

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Stress (f) (MPa)	0.000	9.000	14.490	20.160	24.420	27.300	29.030	29.840	30.000
Plastic Strain (ε) (mm/mm) × 10^{-4}	0.000	3.496	6.000	9.000	12.000	15.000	18.000	21.000	23.307

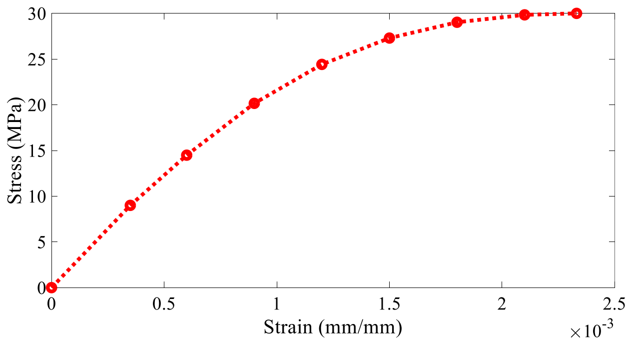

Figure 2. Stress-strain curve for grade 30MPa concrete

2.1.2. Steel Reinforcement

The steel reinforcement in RC columns used in this study consisted of a 12mm diameter bar as longitudinal reinforcement and a 6mm diameter bar as a hoop tie with nominal properties: $E_{se} = 2 \times 10^5$MPa, $E_{sp} = 0.01E_{se}$, f_y =560MPa, f_y' = 290MPa and $v = 0.3$.

2.1.3. FRP Composites

The GFRP composite used in this FE model is assumed to have a nominal thickness of 0.76mm/ply. Table 3 presents the summary of orthotropic material properties of the FRP composites used in the present study.

Table 3. Orthotropic material properties of the GFRP composites [7]

Elastic Modulus (MPa)	Poisson's Ration	Ultimate Strength (MPa)	Shear Modulus (MPa)
$E_x = 65000$	$v_{xy} = 0.31$		$G_{xy} = 1761$
$E_y = 4000$	$v_{yz} = 0.39$	900	$G_{yz} = 1660$
$E_z = 4000$	$v_{xz} = 0.02$		$G_{xz} = 1761$

2.1.4. End Corbels
To subject the column specimens to an eccentric load, end corbels were provided at the extents of the column. The primary function of the end corbel is to transfer load to the column in the test region. In this study, the end corbel was modelled as a single mass element: MASS21. However, the stiffness behaviour of the end corbels was defined as rigid to prevent deformation and damage in the corbels during the solution process. In this model, a modulus of 200,000MPa was used for the end corbels.

2.2. Modelling and Meshing of Rectangular RC Columns
The geometry was created in the ANSYS workbench design modeler. Due to the longitudinal symmetry, only one-half of the full-size rectangular column was modelled in this study. A rectangular solid with end corbels was first created with specified dimensions and corner radii. 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 internal 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 because it helps in controlling the number of elements/nodes. An element size of 20mm is used to mesh this model. The adjacent mesh nodes of concrete and steel reinforcements were connected using the node merge tool. Figure 3 shows the finite element model of eccentrically loaded GFRP wrapped rectangular RC columns.

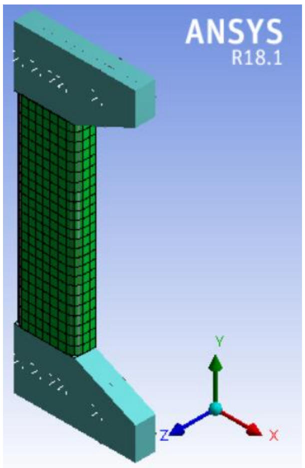

Figure 3. Finite element model of eccentrically loaded GFRP wrapped rectangular RC columns

2.3. 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:

- The bottom surface of the column was sliced according to the location of the fixed support. All the coupled nodes on the bottom sliced line are restrained from all degrees of freedom in three directions.
- The top of the column was sliced according to the location of the applied load. The load was applied normal to the axis of the column.

2.4. Simulation

The ANSYS program employs the Newton-Raphson method to solve problems that involve nonlinear structural behaviour. In the present nonlinear analysis, the automatic load stepping feature was activated, as it enabled the solver to predict and control 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 1/200th of the applied load. The large deflection feature in the solver controls was also activated.

3. Results and discussions

A series of twelve rectangular RC concrete columns wrapped with GFRP under concentric and eccentric loads were analysed in ANSYS 18.1. The variables considered in this FE model include the number of GFRP layers and the intensity of load eccentricity. All the simulated column specimens experienced small deformations. The FEA results are summarised in Table 4.

Table 4. Summary of FE analysis results for the simulated columns

Specimen	Test eccentricity 'e' (mm)	Ultimate load (KN)	Axial displacement at ultimate load (mm)	Yield load (KN)	Axial displacement at yield load (mm)	Ductility index
UW-0ec	0	171	0.530	165	0.423	1.25
1W-0ec	0	181	0.700	174	0.443	1.58
2W-0ec	0	205	0.727	174	0.411	1.77
3W-0ec	0	229	0.736	181	0.388	1.90
UW-15ec	15	135	0.981	123	0.659	1.49
1W-15ec	15	142	1.123	127	0.673	1.66
2W-15ec	15	160	1.189	139	0.644	1.85
3W-15ec	15	190	1.273	150	0.644	1.98
UW-30ec	30	107	1.201	93	0.713	1.68
1W-30ec	30	116	1.379	99	0.735	1.88
2W-30ec	30	138	1.381	110	0.721	1.92
3W-30ec	30	157	1.385	124	0.724	1.91

3.1. Axial Load-Displacement Behaviour

Figure 4 illustrates the load-displacement curves for axially loaded columns. It is evident that the GFRP-wrapped columns experienced a stiffness enhancement with an increase in the number of GFRP wraps. It is also evident that the GFRP wraps have significantly improved the performance and load carrying capacity of the RC columns by increasing their displacement at failure. A maximum load capacity enhancement of 34%, 20% and 6% were realised by columns 3W-0ec, 2W-0ec and 1W-0ec, respectively relative to the unwrapped column.

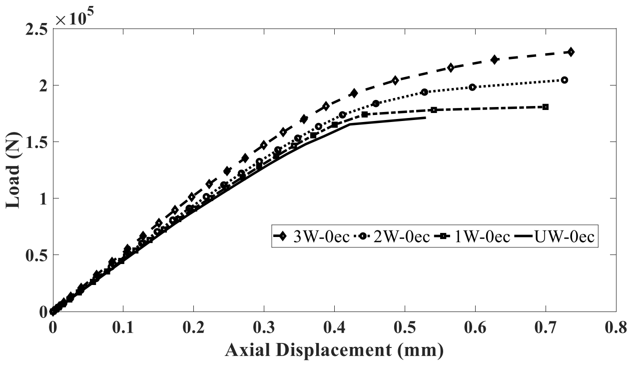

Figure 4. Axial load-displacement curves for the axially loaded columns

The axial load-displacement curves of columns simulated under 15mm of eccentricity are shown in Figure 5. Similar to the axially loaded columns, all the GFRP wrapped columns under 15mm of load eccentricity experienced a significant increase in stiffness with an increasing number of GFRP wraps. Among all the samples, column 3W-15ec achieved the highest maximum load with a 41% enhancement compared to the unwrapped column. Columns 2W-15ec and 1W-15ec achieved a 19% and 5% increase in the maximum load carrying capacity relative to column UW-15ec.

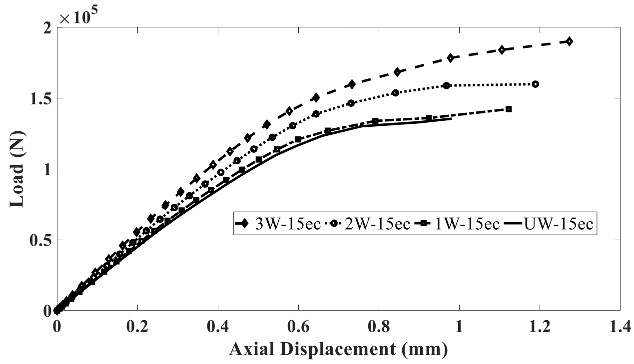

Figure 5. Axial load-displacement curves of the 15mm eccentrically loaded columns

Figure 6 shows the axial load-displacement curves for columns simulated under 30mm of load eccentricity. All the GFRP wrapped columns demonstrated a significant increase in performance and load carrying capacity, as well as stiffness enhancement. A maximum load capacity increase of 46%, 29% and 8% were achieved by columns 3W-30ec, 2W-30ec and 1W-30ec relative to column UW-30ec.

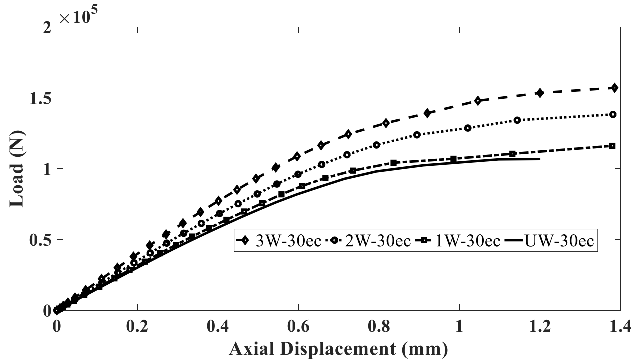

Figure 6. Axial load-displacement curves of the n30mm eccentrically loaded columns

3.2. Ductility

The ductility index was utilised in this FE model to assess the influence of the number of GFRP wraps on the performance of the simulated columns. The ductility index 'μ' of the columns was defined as the ratio of the axial displacement at ultimate load Δ_u to the axial displacement at yield load Δ_y:

$$\mu = \frac{\text{Displacement at ultimate load } \Delta_u}{\text{Displacement at yield load } \Delta_y} \tag{6}$$

When the load drops 20% from the peak load, the ultimate displacement is determined. Alternatively, the yield displacement is specified as the yield of an equivalent bilinear response curve that offers an area equal to that of the response curve, as shown in Figure 7. However, for column specimens without a post-peak behaviour or for when the column failed at the peak point, the last point is used as the ultimate displacement [12], [13]. From Table 4, it is clear that the results of the ductility index have indicated a general increase in the ductility of the strengthened columns.

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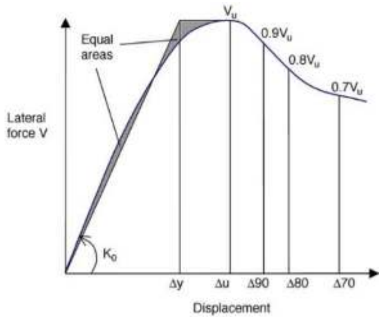

Figure 7. Definition of ductility [13]

3.3. *Influence of Eccentricity*

Figure 9 shows the axial load-displacement curves for columns simulated under different eccentricity of loading. The overall performance of the GFRP wrapped columns increases with an increase in the number of GFRP wraps. However, when the columns are subjected to eccentric loading, the columns experienced a decrease in load carrying capacity and performance.

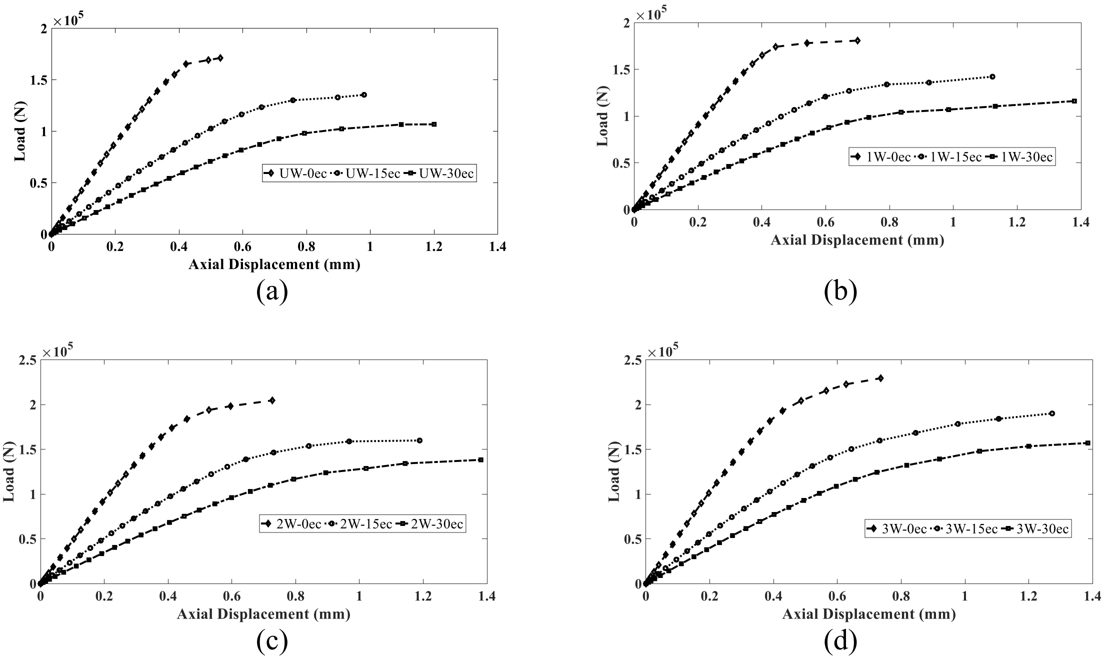

Figure 8. Axial load-displacement curves for columns under different eccentricity of loading

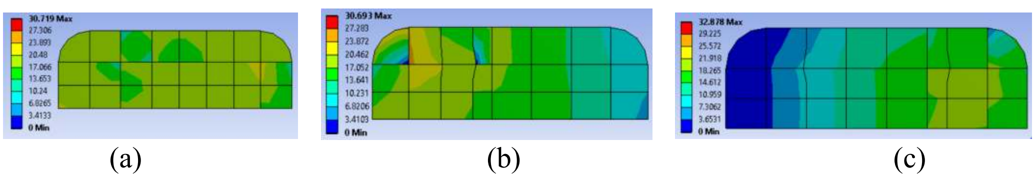

Figure 9. Axial stress distribution in concrete at the plane section of (a) concentrically loaded column (b) eccentrically loaded column (e = 15mm) (c) eccentrically loaded column (e = 30mm)

3.4. *Stress Distribution in concrete at the Plane section of the column*

Figure 8 shows the axial stress distribution in concrete at the plane section of the columns simulated under concentric and eccentric loads. The stress distribution for concentrically loaded columns is maximum at the corners and minimum at the edges of the column section. This stress behaviour aligns with the experimental observations reported by Mirmiran et al. [6], Feng et al. [7] and Youssef et al. [14]. Regarding the eccentrically loaded columns, the stress distribution is maximum in the compression zone and gradually drops to a minimum in the tension zone of the column section.

4. Conclusions

A nonlinear FEA was performed on rectangular RC columns wrapped with GFRP under concentric and eccentric loading. Based on the results, the following conclusions were made:

1. The GFRP wrapping is significant in enhancing the load carrying capacity and ductility of the columns. Columns wrapped with three layers of GFRP wraps achieved the highest maximum load carrying capacity.
2. The GFRP wrapped columns experienced a general loss in load carrying capacity when subjected to eccentricity of loading.

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