3D Finite element modeling of circular reinforced concrete column confined with CFRP under different eccentric loads

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Abstract. This paper presents nonlinear finite element analysis of eccentrically loaded circular Reinforced Concrete (RC) column confined with Carbon Fiber Reinforced Polymer (CFRP). The purpose of this study is to validate the proposed plasticity-fracture model of Piscesa et al. (2019) to model RC column confined with CFRP under eccentric loading. The software used in the simulation is an inhouse finite element package called 3D-NFLEA. Two available specimens in the literature are investigated and an existing numerical result is also included for comparison purposes. From the analysis and investigation, it was found out that the negative effect of confinement at the outer concrete region was caused by significant difference between the concrete dilation rate at the inner to the outer concrete core region. In addition, From the comparison, close agreement between the numerical models and the available test result are discovered in this study. As for the column ductility, it was found out that the column ductility was higher for column with larger initial load eccentricity.

1. Introduction
Carbon Fiber Reinforced Polymers (CFRP) are a solution for external retrofit applications that have become popular and are widely used in structural retrofitting. Carbon Fiber Reinforced Polymers (CFRP) have advantages such as being lightweight, high strength, and easy to implement in the field [1]. By using CFRP in the potential plastic hinge area region [2], the lateral deformation capacity of RC column can be increased. When the plastic hinge formed in RC column, the column may exhibit reduced load carrying capacity. Increase in the lateral deformation capacity of CFRP confined concrete is caused by the confinement effect of the CFRP jacket which enhance both the concrete core strength and ductility [3-7]. The enhanced lateral deformation capacity of CFRP confined RC column allows the concrete material within the plastic hinge region to remain intact at large deformation cycles [8-11]. Since CFRP is added later to retrofit the column, the CFRP element is considered here as the external confining devices. (see Piscesa et al. [12]).

From the available study, many investigations of CFRP confined RC column have been focused on its behavior under concentric load [6, 13-15]. These studies showed that the retrofitting method was successful in increasing the strength and ductility of RC column. However, more research work is
necessary to investigate the behavior of CFRP confined RC column in detail under eccentric loading condition. This eccentric load condition will enable strain gradient in the cross section and thus resulted in more complex behavior of the concrete material under unequal confinement condition.

In this paper, CFRP confined RC columns under eccentric loading are investigated. An inhouse 3D-NLFEA finite element package [16, 17] is used in the numerical simulation. The concrete constitutive model is based on the Piscesa et al. [12, 18] plasticity-fracture model which is restraint sensitive and path-dependent. The model can predict plastic-volumetric compaction which is important to capture the concrete behavior where both high confining pressure and high stiffness of confining devices are present [19]. The constitutive model for the steel solid material and the reinforcing bars obeys the \( J_2 \) metal plasticity model. While the FRP material is modeled as an elastic transversely orthotropic material.

Since the loading considered in the analysis is concentric, it is wise to include the \( 2^{nd} \) order effect in the analysis. The \( 2^{nd} \) order effect analysis will account for the geometrical change in the column due to additional eccentricity. From the previous study [20-22], 3D-NLFEA was successful in capturing the behavior of Concrete Filled Steel Tube (CFST) column under concentric and eccentric loads which involves the \( 2^{nd} \) order effect in the analysis. For comparisons purposes, two specimens from Bisby and Ranger [23] are investigated. In addition, numerical result with the same specimens carried out by Lin and Teng [24] are included in the analysis. This paper discusses the lateral modulus contour distribution both in the elastic stage and after the ties is yield. Comparisons of axial load as function of the lateral mid-height displacement curves between the model and the test results will be presented. Finally, ductility evaluation of the CFRP confined RC column is briefly discussed.

2. Constitutive model of material

Figure 1 shows the stress-strain diagram for the CFRP, rebar, and steel loading plate materials. In the finite element model, the CFRP element was modeled as an elastic transversely orthotropic material. An elastic-fracture constitutive model is used for the CFRP element. The softening modulus is set to one-fourth of the hardening modulus to prevent sudden drop of stresses in the CFRP elements. The fiber orientation is set to be oriented in the hoop’s direction. The elastic modulus for the CFRP element which consisted only for the resin modulus is set to at least ten percent of the CFRP elastic modulus but not more than 10 GPa. The rebar is modelled using embedded truss element which obey the elastic perfectly plastic model. There is no strain hardening considered and buckling of longitudinal bars are not considered in the analysis. The steel loading plate is modelled as solids element which follows the \( J_2 \) metal plasticity model with no strain hardening behavior considered.

![Stress–strains diagram of specimen materials.](image)

The concrete material is based on the plasticity-fracture model developed by Piscesa et al. [12, 18]. In a way, the used plasticity-fracture model is similar in theory with [25] but differs in term of the compression plasticity model. For passively confined concrete, a model which is not only pressure dependent but also restraint sensitive should be used to correctly capture the behavior in the tested specimen. Here, the restraint sensitiveness of the plasticity-fracture model is determined from the lateral modulus value obtained from the analysis during the simulation. From previous study [16], it was shown that the use of plasticity-fracture model [12, 18] can accurately predict the response of CFRP confined RC column under concentric loading. However, further validation for non-uniform confining pressure
should be carried out. This paper also serves as a validation of the Piscesa et al. [12, 18] plasticity-fracture model to predict the behavior of CFRP confined concrete under eccentric loading. Inside the 3D-NLFEA finite element package, it is important to note that the return mapping algorithm for the plasticity-fracture model was based on two nested algorithm of multi-surface plasticity model [17].

3. Reinforced concrete column model

3.1. Specimen geometry detail

The modeled specimens are obtained from Bisby and Ranger [23] with eccentricity value 30 and 40 mm. This specimen is noted as C30 and C40 in this paper. 3D-NLFEA uses SALOME platform [26] to prepare the geometry of the model and to mesh the model. The meshed model is then extracted as an input in 3D-NLFEA. Figure 2 shows the geometrical interpretation of the specimens. As shown in Figure 2, the specimen diameter is 152 mm while the specimen height is 608 mm. The load eccentricity considered are 30 and 40 mm. The longitudinal bar consisted of four bars with 6.4 mm diameter. The confining bar had the same diameter as the longitudinal bar. The pitch spacing of the longitudinal bar is 100 mm (see Figure 2b for more details). The FRP thickness for one ply is 0.38 mm.

The concrete strength of the specimens is 33.2 MPa for compression and 3.557 MPa for tensile. The modulus of elasticity for the concrete is 20431.1 MPa. The CFRP material have a yield tensile strength of 933 MPa, ultimate tensile strength of 1014 MPa, elastic modulus of 90000 MPa, rupture strain of 1.12 % and the Poisson’s ratio of 0.3. The yield strength of the bar is 710 MPa while the Young’s modulus is 200 GPa. The steel loading plate is considered to have the yield strength close to that of A36 steel material.

At both ends, a 25 mm thick steel loading plate is used to distribute the knife-edge load from the steel to concrete. This steel plate is required to avoid stress concentration due to sharp displacement control at the top end. A thin line of displacement control is set at the top steel loading plate while at the bottom plate, a thin line of restraint is provided in all direction. Schematic details on the boundary conditions are shown in Figure 2 (c).

Figure 2. Side view and cross section of specimen.

3.2. 3D Modeling of Specimen
The 3D model of RC columns is prepared using SALOME 9.3.0 [26] as shown in Figure 3. The total number of solid elements is 27,702 and 27,084 are used to model C30 and C40 columns, respectively. The concrete, CFRP and reinforcing bars elements are shown separately as shown in Figure 3 (a), (b) and (c), respectively. The full meshed element of the specimens as shown in Figure 3 (d). The knife-edge load at the top end, which act as a displacement control during the numerical analysis, can be moved with different eccentricities while at the bottom, a fixed restraint boundary condition is sought.

![Meshed model of a typical column under eccentric loading.](image)

4. Analysis results and discussions

4.1. Lateral modulus contour distribution

In this section, the lateral modulus for RC columns confined with CFRP members is being examined in detail to understand more about the confinement effectiveness. The focus of investigation is on the development of the lateral modulus in the elastic phase and when the transverse steel is yielded. The lateral modulus was found to be the highest at the concrete core due to the circular ties and the CFRP jacket work together to confine the inner concrete core (see Figure 4 (a)). On the other hand, the outer concrete core only confined by CFRP and thus have lower lateral modulus value due to less confined behavior. This indicates that the effectiveness of the CFRP may not be fully functioning before the circular ties is yields.

The 3D surface of the lateral modulus contour at the elastic phase for specimen C30 and when the steel ties are yielded are shown in Figure 4 (a) and (b), respectively. The lateral modulus value in the inner concrete core is higher than that of the outer concrete core. At the ties level, for concrete area under compression, there is a high value of lateral modulus concentration as shown in Figure 4 (a). This shows that the circular ties stiffness is more concentrated than the CFRP. Arching actions between the ties are clearly shown and was associated with the steel ties. Outside the arches, the lateral modulus is lower than the one exerted by the CFRP wrap. This condition would give different concrete dilation rate between the two core regions. Since at the outer concrete core the concrete dilation rate is much higher than the inner core, there will be a negative effect in the outer concrete core. Hence, the value of the lateral modulus at the outer region will be less than the one exerted by the CFRP wrap if it was used as a single confining device. Figure 4 (b) shows when the lateral modulus between the ties where it is drops and only occurs in the compressed region of the concrete. This shows that, the CFRP tubes starts to effectively confine the concrete.
Figure 4. The C30 specimen volume with the lateral modulus contour.

Figure 5. The C40 specimen volume with the lateral modulus contour.

Figure 5 (a) shows the lateral modulus contour and the 3D surface at elastic stage and Figure 5 (b) shows the same condition when the steel ties are yielded for specimen C40. Similar conclusions were obtained from specimen C30 for specimen C40, as shown in Figure 5.

4.2. Comparisons with experimental result

Figure 6 shows the comparisons between the numerical models and the test results for specimen C30 and C40 in terms of axial force versus additional eccentricity at the mid-height for C30. In Figure 6, the FEA results carried out by Lin et al. [24] was executed using ABAQUS finite element software package. The concrete constitutive model in [24] was from [27, 28]. As shown in Figure 6(a), the initial stiffness
response from 3D-NLFEA, test result, and from [24] are similar. At lateral displacement about 2 mm, the axial load from both 3D-NLFEA and [24] are higher than the test result. However, at lateral displacement around 11 mm, the axial load from 3D-NLFEA is in good agreement with the test result, while the axial load from [24] was found to be higher than the test result. The same conclusion was found for specimen C40 as shown in Figure 6(b).

![Figure 6. Comparison of axial load–lateral displacement curves of columns.](image)

### 4.3. Ductility of column
The evaluation of column ductility is based on the $I_{10}$ ductility index which is based on the energy ratio. The $I_{10}$ ductility index was proposed by Foster and Attard [29] in which often used to estimate the flexural toughness of beam in ASTM C1018 [30]. In the research of Samani et al. [31], the $I_{10}$ ductility index was used to evaluate the ductility of RC columns. This energy is computed as the area beneath the moment-curvature curve ($M$-$\phi$). The bending moment is obtained by multiplying the axial load ($P$) with the total lateral mid-height displacement ($\Delta$). By taking the value of the strain that occurs in the mid-height cross section (zero axial strain) of the column then dividing it by the distance between the measured axial strain value to the neutral line of the cross section, the curvature value is obtained from Paraview 5.8 (post-processor, see [32, 33]). To get the value of $I_{10}$, one can compute the area ratio of the $M$-$\phi$ from the analysis (point OCD) to the area of triangle OAB (see Figure 7).

Table 1 shows the value for the $I_{10}$ ductility index for both columns. As shown in Table 1, the $I_{10}$ ductility index for specimen C30 is lower than specimen C40. As the load eccentricity increased, the ductility of column becomes higher. This can be well understood as the compression in concrete is less and therefore the column behaves more like a beam and therefore more ductile. Several researchers [34-37] have performed ductility tests of concrete columns applied to conventional concrete and CFRP reinforced concrete columns at eccentric loads.

**Table 1. Ductility index of RC column.**

| No. | Specimens ID | $I_{10}$ |
|-----|--------------|---------|
| 1   | C30          | 8.284   |
| 2   | C40          | 8.434   |
5. Conclusions

This paper presents full three-dimensional nonlinear FEA of circular reinforced concrete column confined with CFRP under different eccentric loads. The FEA are carried out using the 3D-NLFEA program developed by the Piscesa et al. A plasticity-based constitutive model developed by Piscesa et al. is used for the concrete material under compression and fracture-plasticity based constitutive model developed by Piscesa et al. (2019) for concrete material under tension. Two test results available in the literature from Bisby and Ranger (2010) are investigated.

From the analysis and investigation, it was found out that the significant difference between the concrete dilation rate at the inner to the outer concrete core region caused by a negative effect of confinement at the outer concrete region. The negative confinement effect can be attributed to the following: in the ties level for concrete area under compression there is a concentration of lateral modulus (at the elastic phase). However, the concentration of the lateral modulus at ties level disappears when the circular ties is yield. From the comparisons between the models and the test results showed that the 3D-NLFEA prediction agrees well with the test result. As for the column ductility, it was found out that the column ductility was higher for column with larger initial load eccentricity.

Further research should be focused on more comparisons with the experimental data which cover different load eccentricity, dimension, and strength of material properties. It should also be noted that the material data inputed in the analysis is a mean data extracted from the experiments. In practice, there are possibilities of having variations in the material strength which may result in lower material strength. Thus, further research is needed to investigate RC columns confined with CFRP under different eccentric loads and it is necessary to investigate in detail on the confining pressure distribution.

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