Numerical modeling of low strength reinforced concrete column strengthened with CFRP jacketing

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Abstract. Reinforced concrete column strengthened with Carbon Fiber Reinforced Polymer (CFRP) has been investigated numerically. Reinforced concrete column with low compression strength is used in this study. Concrete column is modeled by 3D solid elements with 8 nodes linear brick elements (C3D8R), whereas reinforcement bars modeled by 3D truss elements with 2 nodes first order elements (T3D2). In order to simulate concrete response in the specimen, concrete damage plasticity model with specifying damage parameters in both of compression and tension has been adopted in this paper. The specimen is subjected to uniaxial compression loading applied with displacement-controlled method. The effects of CFRP jacketing on reinforced concrete column with low compression strength are observed. The characteristic of reinforced concrete column combined with CFRP in terms of load-displacement behaviour and stress distributions are also evaluated. It is found that the numerical technique proposed in this study is quite efficient to predict the behaviour of low strength reinforced concrete column strengthened with CFRP with regard to the ultimate load, CFRP strain, and concrete strain distribution.

1. Introduction

Concrete materials is the most common materials found in many construction industries for decades due to its high strength capacity and durability relative to its cost. The tensile strength of concrete materials is limited, so crack formation, which can endanger its durability, may occurred at any stages from service life of concrete structures. These cracks can penetrate into the mortar matrix and later on reduced the mechanical properties of concrete materials. Recent researches showed that an incoming crack and embedding additional materials into the mortar matrix of concrete could significantly reduce the mechanical properties of concrete [1, 2, 3].

Based on comprehensive literature reviews, a number of existing reinforced concrete columns may indicate inadequate capacities with regard to materials quality, reinforcement and detailing especially when compared to the current SNI-2847:2013 (Indonesian Standard)-codes. They are predicted to be performed very poor especially when subjected to the extreme loadings, such as earthquake loading.
Retrofitting such poor columns with Fiber Reinforced Polymer (FRP) may upgrade their performance to meet the capacity requirements in the current concrete codes [4]. Some researches in FRP found that the ratio between the effective strain and FRP tensile strength is the significant factor in FRP jacketing [5] and concrete materials using recycled aggregates with low compressive strengths have influenced the damage patterns in FRP layers [6, 7]. However, a problem arises when the concrete strength found in the existing concrete is very low comparing to the minimum compressive strength required for concrete structures based on SNI-2847:2013 is 17 MPa. According to ACI 440 2R 17, using Carbon Fiber Reinforced Polymer (CFRP) as strengthening materials, the minimum allowable compressive strength of concrete materials is 17 MPa [10].

The effect of low compressive strength on global mechanical properties of concrete structures is still unknown and quite interesting to investigate. The recent researches confirmed that the possibility of concrete with low compressive strength is strengthened with CFRP. It showed that the compressive capacity of concrete has increased significantly [5, 7]. Based on that reason, the objective of this paper is to investigate numerically the effect of low strength reinforced concrete column strengthened with CFRP jacketing subjected to compressive axial loads. The behaviour of concrete column with three different cases, such as plain concrete, reinforced concrete, and reinforced concrete with CFRP, are adopted in this study. The numerical model with nonlinear analysis in Abaqus was applied and used in the simulations.

2. Methodology

2.1. Design of test specimens

In this study, the concrete compressive strength of 7 MPa, which is very low strength, was adopted. The concrete column specimen has dimensions of 250x250x1680 mm, with 4D13+8D10 longitudinal reinforcement ($\rho_s = 1.8548 \%$). The shear reinforcement used is square stirrups with cross ties, transverse bars using a plain 8 diameter with a spacing of 50 mm ($\phi_8 - 50$), mounted on the plastic hinge zone with height $h = 250$ mm, whereas the stirrups in the outside plastic hinge zone are reinforced with plain 8 diameter square stirrups with a spacing of 95 mm ($\phi_8 - 95$), without cross ties. Slenderness effect of column resulting in a second order effect is not considered, because the column geometry is designed with a slenderness factor of $kl/r=22$. The detailed variable and configuration specimens are shown in table 1 and figure 1, respectively.

| Specimens | Compressive strength (MPa) | Axial Deformation (mm) | explanation          |
|-----------|---------------------------|------------------------|----------------------|
| C7P       | 7                         | 50                     | Plain concrete specimens |
| C7R       | 7                         | 50                     | Reinforced concrete specimens |
| C7R+C     | 7                         | 50                     | RC+CFRP specimens     |

The concrete column specimen C7R+C is a reinforced concrete column specimen strengthened with 2 plies CFRP, installed along the height of the column. figure 2 shows the detailed installation of CFRP along the specimen.
2.2. Modelling of Concrete Column
The methodology used in this study is numerical modeling of reinforced concrete column strengthened with CFRP. Concrete column is modeled by 3D solid elements with 8 nodes linear brick elements (C3D8R), while the embedded reinforcement bars modeled by 3D truss elements with 2 nodes first order elements (T3D2). CFRP is modeled as a deformable 3D shell element (S4R). The behavior of CFRP materials is modeled as elastic linear with lamina type. The interaction between CFRP and concrete is considered to be perfectly bond by selecting the Tie constraint type, by considering the concrete as the master surface and CFRP as the slave surface. CFRP has a thickness of 0.166 mm.

The supports of the column were assumed to be fixed at the bottom and free at the top of the column. The load is applied at the top of the column with an axial displacement of 50 mm, as illustrated in figure 4. This specimen is subjected to monotonic axial load applied with displacement-controlled method. In order to simulate concrete response in the model, concrete damage plasticity model with associated tension and compression damage parameters was adopted in this study. The material properties of concrete specimens, reinforcement bars, and CFRP as depicted in table 2 to table 5 are used in this simulation. Concrete damage plasticity model (CDPM) for the compressive
behaviour based on modified Mander formulas [8], whereas for the tensile behaviour based on Wahalathantri formulas [9].

The equation of compressive stress-strain model used with Mander modification is as follows:

\[ f_c = \frac{f_c' x r}{r - 1 + x r^\beta} \quad (\text{MPa}) \]

\[ \beta = \left( \frac{f_c' + 23}{38} \right)^{0.45} \]

\[ x = \frac{\varepsilon_c}{\varepsilon_c'} \]

\[ r = \frac{E_c}{E_c - E_{sec}} \]

\[ E_c = 5000 \sqrt{f_c'} \quad (\text{MPa}) \]

\[ E_{sec} = \frac{f_c'}{\varepsilon_c'} \quad (\text{MPa}) \]

\[ \varepsilon_c' = 0.00003 f_{cmax} + 0.001 \]

Where \( f_c' \) is compressive strength of concrete at 28 days, \( \varepsilon_c' \) is the value of the peak strain when the stress reaches \( f_c' \), and \( \varepsilon_c \) is the strain that occurs. The equation of the tensile stress-strain model using the Wahalathantri modification is as follows:

\[ f_t = 0.3 f_c'^{2/3} \quad (\text{MPa}) \]

\[ \varepsilon_{cr} = \frac{f_t}{E_c} \]

Where \( f_t \) is the tensile strength of concrete at 28 days, \( \varepsilon_{cr} \) is the value of the peak tensile strain when the stress reaches \( f_t \).

\[ \text{Figure 3. Concrete Tensile Stress-Strain Behavior} \]
Table 2. Material properties for concrete.

| Concrete elastic | Plasticity parameters |
|------------------|-----------------------|
| $E$ | $v$ | Dilation angle | 30.5 |
| 13228.8 | 0.19 | Eccentricity | 0.1 |
| | | $f_{ys}/f_{c0}$ | 1.16 |
| | | $K$ | 0.67 |
| | | Viscosity parameter | 0.001 |

Table 3. Material properties for Steel in class BJTD40.

| Elastic | Plastic |
|--------|---------|
| $E$ | $v$ | Yield Stress | Crushing strain |
| 200000.0 | 0.3 | 400.0 | 0.000 |
| | | 500.0 | 0.088 |

Table 4. Material properties for Steel in class BJTD24.

| Elastic | Plastic |
|--------|---------|
| $E$ | $v$ | Yield Stress | Crushing strain |
| 200000.0 | 0.3 | 240.0 | 0.0000 |
| | | 300.0 | 0.1188 |

Table 5. Material properties for CFRP model.

| Young's modulus | Poisson ratio | Shear modulus |
|-----------------|--------------|---------------|
| $E_1$ | $E_2$ | $v_{12}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ |
| 170000 | 9000 | 0.35 | 4800 | 4800 | 4500 |

Figure 4. Mesh Model (a) Column Specimen, (b) CFRP
3. Results and discussions

3.1. Load-displacement curves
The simulation results show that the maximum axial load \( P_{\text{max}} \) of the column specimen C7P is 560 KN and its corresponding displacement \( \Delta \) is 2.9 mm. After the load reaches its peak, the load carrying capacity of the specimen starts to decrease until the end of loading, as can be seen in figure 5.

**Figure 5.** Load-Displacement of uniaxially loaded in plain concrete specimens.

The maximum axial load \( P_{\text{max}} \) of the column specimen C7R is 1171 KN and its corresponding displacement \( \Delta \) is 4.6 mm. After the load reaches its peak, the load carrying capacity of the specimen starts to decrease until the end of loading, as can be seen in figure 6.

**Figure 6.** Load-Displacement of uniaxially loaded in reinforced concrete specimens.

The maximum axial load \( P_{\text{max}} \) of the column specimen C7R+C is 1505 KN and its corresponding displacement \( \Delta \) is 15.9 mm. After the load reaches its peak, the load carrying capacity of the specimen starts to decrease until the end of loading, as can be seen in figure 7.
Figure 7. Load-Displacement of uniaxially loaded in RC+CFRP specimens.

Figure 8 shows the load-displacement curves from three different specimens, such as plain concrete, reinforced concrete, and reinforced concrete with CFRP.

Output from simulation results that quite interesting to discuss is load-displacement curves from three different specimens. As can be seen from figure 8, the load carrying capacity from plain concrete has the lowest value compared to the others, while reinforced concrete strengthened with CFRP has the highest. The summary of simulation results for each specimen is shown in table 6.

| specimens | Peak Load (kN) | Displacement (mm) | Strength Increase Ratio | Percentage of increase (%) |
|-----------|----------------|-------------------|-------------------------|----------------------------|
| C7P       | 560            | 2.9               | 1                       | 0                          |
| C7R       | 1171           | 4.6               | 2.1                     | 109                        |
| C7R+C     | 1505           | 15.9              | 2.7                     | 169                        |
3.2. Deformation shapes

The deformation shape of plain concrete specimen is dominated by vertical displacement since there is no steel reinforcement embedded inside the concrete materials. The maximum stress occurred from the midspan to the bottom of the concrete as can be seen from figure 9.a. The deformation shape of reinforced concrete specimen is quite different from the plain one. The confinement effect from shear reinforcement clearly shows its phenomenon. The cross ties applied near the bottom affects concrete to have plastic hinge around it. The maximum stress typically occurred in the midspan when bending moment existed as shown in figure 9.b. The reinforced concrete strengthened with CFRP shows a sufficient behaviour compared to the plain and reinforced concrete. figure 9.c shows that the effect of CFRP on deformation shape of the concrete is quite significant. The actual stress of concrete with CFRP is the lowest compared to the plain and the reinforced concrete. It also shows that CFRP is able to distribute stress, so there is no stress accumulated in the specific area of the concrete as shown with the colour of the contour.

(a) plain concrete specimens.  (b) reinforced concrete specimens.  (c) RC+CFRP specimens.

Figure 9. Deformation shapes of uniaxially loaded (DAMAGEEC).

4. Conclusions

The numerical modeling of reinforced concrete column strengthened with Carbon Fiber Reinforced Polymer (CFRP) has been investigated in this study. The concrete column with low compressive strength of 7 MPa was used in the model. Three different cases of specimen are considered in this study, such as plain concrete, reinforced concrete, and reinforced concrete strengthened with CFRP. The simulation results showed that reinforced concrete strengthened with CFRP has the highest maximum load carrying capacity compared to the plain and reinforced concrete. Furthermore, CFRP applied in concrete has significant effect in increasing the ductility of materials. The simulation results on column specimens with very low strength concrete (7 MPa) actually provide a pretty good picture of increasing its maximum load capacity, and still have great potential to be strengthened with CFRP.

The results in this study are based only on uniaxial loading applied on the specimens. The effect of lateral load on the load carrying capacity of the materials should be investigated in the future. The fracture behaviour of concrete column strengthened with CFRP should be also studied by incorporating crack model into numerical model.
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