SEISMIC PERFORMANCE OF GFRP-RC RECTANGULAR COLUMNS: NUMERICAL STUDY

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Composite materials like glass fiber-reinforced polymer (GFRP) is becoming widely acceptable to be used as a reinforcing material due to its high ultimate tensile strength-to-weight ratio and excellent resistance to corrosion. However, the seismic behavior of GFRP-reinforced concrete columns has not been fully investigated yet. This paper presents the results of a numerical analysis of full-size GFRP-RC rectangular columns under cyclic loading. The simulated column depicts the lower part of a building column between the foundation and the point of contra-flexure at the mid-height of the column. GFRP reinforcement properties and concrete modeling based on fracture energy have been incorporated in the numerical model. Experimental validation has been used to examine the accuracy of the constructed finite element models (FEMs) using a commercially available software. The validated FEM was used to perform a parametric study, considering several concrete strength values and axial load levels, to study its influence on the performance of the GFRP-reinforced concrete columns under cyclic loading. It was concluded that the hysteretic dissipation capacity deteriorates under high axial load level due to severe softening of the concrete. The FE results showed a substantial improvement of the lateral load-carrying capacities by increasing concrete compressive strength.

Keywords: GFRP reinforcement, Internal reinforcement, Aspect ratio, Cyclic loading, Parametric study, Finite element modelling.

1 INTRODUCTION AND BACKGROUND

Reinforced concrete (RC) columns are one of the structural components of the seismic-force-resisting systems that are widely used in earthquake-prone areas. RC columns under cyclic load have complex non-linear hysteretic response. Once a column fails during an earthquake, the entire structure suffers severe damage or even collapse. Therefore, it is necessary to investigate the seismic performance of columns to understand their behavior during earthquake excitations.

The implementation of fiber-reinforced polymer (FRP) composites as reinforcement in RC structures has increased significantly in the last decade, primarily because of their noncorroborable nature. Moreover, as compared to steel reinforcement, FRP reinforcement has many desirable properties such as high strength-to-weight ratios, reasonable fatigue strength, high electromagnetic transparency, and low relaxation characteristics (Ferdous et al. 2020). The GFRP bars are more economical than the other available FRP types, thus, they are more attractive for infrastructure applications. Compared to steel, GFRP reinforcement do not exhibit a yielding plateau; instead, it behaves elastically until they fail at a higher tensile strength.

Recently, experimental research studies on concrete columns reinforced with GFRP under simulated seismic loads have been conducted to investigate various variables and design parameters (Ali and El-Salakawy 2015, Naqvi et al. 2017, Sheikh and Kharal 2018, Abdallah and
El-Salakawy 2021). Tests showed that a softer response occurred by using GFRP longitudinal bars, resulting in significantly lower shear and moment capacities to steel-RC columns counterparts (Ali and El-Salakawy 2015, Elshamandy et al. 2018).

An acceptable level of energy dissipation under low axial load levels compared with steel-RC columns is provided by GFRP-RC ones (Ali and El-Salakawy 2015, Elshamandy et al. 2018). The GFRP-RC columns had an equivalent deformability to the ductility of the steel-RC counterparts.

Tie configuration and spacing plays a crucial role in determining the behavior of square columns (Sheikh and Kharal 2018). Few numerical studies were conducted to address RC members or assemblies reinforced by of FRP (Ghomi and El-Salakawy 2018, Attia et al. 2020).

The aim of this study is to examine the seismic behavior of GFRP-RC rectangular columns using the non-linear finite element analysis (FEA) software ATENA/GID (Červenka et al. 2018). The finite element model (FEM) was validated against the previous experimental results by Ali and El-Salakawy (2015), then was used to investigate the influence of concrete strength and level of axial load on the column performance.

2 SUMMARY OF EXPERIMENTAL INVESTIGATION

2.1 Test Specimens and Material Properties

Ali and El-Salakawy (2015) performed an experimental research study on eight 350-mm wide square columns with 1,650 mm shear span (Figure 1). The study was carried out to investigate the seismic behaviour of GFRP-RC square columns under different parameters like reinforcement type (steel and GFRP), longitudinal reinforcement ratio, axial load level and the tie spacing. Further information regarding the design of the experimental specimens can be found elsewhere (Ali and El-Salakawy 2015).

2.2 Test Setup and Procedure

All specimens were subjected to a uniaxial reversed-cyclic lateral load in addition to constant axial load, as shown in Figure 1. The concentric vertical axial load was applied by means of 1000 kN capacity hydraulic jack. Using a 1000-kN capacity, 250-mm stroke hydraulic actuator, the lateral load was applied at the column tip on two phases. Phase 1, load-controlled, consisted of two load cycles: a cracking cycle followed by a service cycle. In Phase 2, displacement-controlled, the simulated seismic load was implemented in several displacement steps at a rate of 0.01 Hz. The seismic load was adopted from the ACI Committee 374 report on the acceptance criteria for moment resisting frames based on structure testing (ACI 2005).

3 NUMERICAL MODELLING

Three-dimensional (3D) finite element models have been constructed to simulate the nonlinear seismic behavior of the tested columns using the software package ATENA 3D (Červenka et al. 2018). Both geometrical and material non-linearity were considered in the numerical model. The mechanical properties of the materials reported earlier that were tested in the experimental program were used as input data in the 3D model (Figure 2).
Figure 1. Experimental test setup - typical dimensions, cross-sections and reinforcement details of specimens (Reproduced from Ali and El-Salakawy 2015).

3.1 Material Modeling

3.1.1 Concrete

Eight-node brick elements were used for the 3-D modeling of concrete geometry, while the concrete material was modeled using a built-in fracture-plastic constitutive model. This constitutive model incorporates both tensile (fracture) and compressive (plastic) concrete behaviour models. The default formulas for calculating the concrete parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder strength</td>
<td>( f_c' = 0.85 f_{cu} )</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>( f_t' = 0.24 \left( f_{tu} \right)^{2/3} )</td>
</tr>
<tr>
<td>Initial elastic modulus</td>
<td>( E = \left( 6000 - 15.5 f_c' \right) \sqrt{f_c'} )</td>
</tr>
</tbody>
</table>

Where \( f_{cu}' \): Cube concrete strength.

3.1.2 Reinforcement materials

Using truss elements, the steel and GFRP reinforcements were modelled as discrete one-dimensional reinforcing bars. Linear and bilinear stress-strain relationships for GFRP and steel reinforcement, respectively, were used (Červenka et al. 2018). The Bauschinger effect on reinforcement under cyclic loading was implemented by using Menegotto–Pinto model.
Steel reinforcement model was incorporated by means of bilinear law, elastic-perfectly plastic, while, GFRP reinforcement was modeled with a linear behavior up to its ultimate tensile strength.

### 3.1.3 Geometry and boundary conditions

To simulate the boundary conditions of the experimental test specimens, two strips of the bottom steel plate were restrained against movement in all directions as shown in Figure 2. Two identical strips were provided on top of the footing to simulate the supporting effect of the Dywidag bars used to fix the footing to the laboratory’s floor during testing. In all models, the macro-elements were meshed into cubic elements with side length of 100 mm.

### 3.2 Finite Element Model Validation

The hysteretic behavior results obtained by the FEA validated against the experimental results by Ali and El-Salakawy (2015) are shown in Figure 3. One steel-RC specimen and two GFRP-RC ones were selected for the validation process, as listed in Table 2. These specimens were selected to demonstrate the applicability of the FEM to both steel and GFRP-RC columns.

Table 2. Details of the test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Reinforcement type</th>
<th>Longitudinal reinforcement (%)</th>
<th>Axial load level (%)</th>
<th>Stirrup spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1.3-10-75</td>
<td>Steel</td>
<td>1.31</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>G-1.3-10-75</td>
<td>GFRP</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G-1.9-10-75</td>
<td>GFRP</td>
<td>1.94</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2. Geometric model of test specimens](image)

![Figure 2. Boundary condition at top and bottom of footing](image)

**3.3 Effect of Concrete Strength and Axial load Level**

Based on the validation process carried out, the constructed FEM was able to reliably predict the experimental results of the tested columns. The validated FEMs were used to study the effect of concrete strength and the axial load level on the seismic behavior of GFRP-RC columns. The study focused on the drift ratios up to 4%, which agrees with the recommendations of the
CSA/S806-12 (CSA 2017) that require a deformable moment-resisting FRP-RC frame to be able to withstand 4% drift ratio.

### 3.3.1 Concrete strength

Investigated FE matrix has compressive strengths ranging between 30 and 80 MPa with 10 MPa increments. As expected, the specimen with the lowest concrete strength (30 MPa) had the lowest lateral load capacity. Increasing the concrete strength from 30 to 80 MPa resulted in a 52% increase in the lateral load capacity at 4.0% drift ratio as shown in Figure 4a.

### 3.3.2 Axial load level

The axial load level is represented by $P/(Acf_c')$, where $P$ is the concentric axial load, $Ac$ is the gross area of column section, and $f_c'$ is the concrete compressive strength. Figure 4b shows the envelopes of the lateral load-drift ratio relationship for all eight specimens. Increasing the axial load level increased the pinching distance at the same drift ratio. At low axial load levels (i.e., 10 and 20%), the lateral load capacity increased gradually up to a drift ratio of 4.0%. When the axial load level was further increased to 30, 40, 50 and 60%, the maximum lateral load capacity was reached at a lower drift ratio of 3.0, 2.0, 2.0, and 1.5%, respectively. In addition, increasing the axial load level decreased the drift capacity of the columns with the columns subjected to higher axial load levels failed at considerably lower drift ratios. Therefore, high axial load levels can influence the mode of failure and limit the ability of columns to reach higher drift ratios.

![Figure 3](image_url)

**Figure 3.** Experimental hysteretic behavior against the analytical of the specimens.

![Figure 4](image_url)

**Figure 4.** Envelopes of the hysteretic response.

### 4 CONCLUSIONS

Based on the conducted FEA study, the following conclusions can be drawn:

1. An improvement in the lateral load capacity of the GFRP-RC column by 52% was achieved by increasing the concrete compressive strength from 30 to 80 MPa increased.
2. Increasing the axial load level has an insignificant influence on the behaviour of GFRP-RC columns at low drift ratios (less than 1%). However, increasing the axial load level decreased the drift capacity of the columns with the columns subjected higher axial load levels failed at relatively low drift ratios.

3. At low axial load levels of 10 and 20% of the column axial capacity, the lateral load capacity increased gradually until failure. Nonetheless, when the axial load level was increased to 30, 40, 50 and 60%, the maximum lateral load capacity was reached at a lower drift ratio of 3.0, 2.0, 2.0 and 1.5%, respectively.

Acknowledgments
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References
ACI, Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary, ACI 374-05, American Concrete Institute (ACI), Detroit, American Concrete Institute, 13, 2005.