Performance of Reinforced–Concrete Frame with Embedded FRP rod

Ahmed Abdulrahman Ftaikhan, F. Hejazi*, Raizal S.M. Rashid, Nima Ostovar

Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

*farzad@fhejazi.com

Abstract. Most of the researchers have mainly focused on using of FRP rod to repair, retrofit and using it as additional strength besides steel rebars in structural which have a lack of lateral loading resistance. Application of using FRP rod as the main reinforcement is still rarely used in many areas, especially in the strengthening of the Structure. In present study, nonlinear finite element models have been developed by ABAQUS software to evaluate the effect of using CFRP rod and GFRP rod instead of steel rebars on efficiency of frame to prevent the seismic effect. Also, verifying is conducted by development nonlinear finite element models using ARCS3D software and compare with Experimental Results. Numerical results show superior performance of CFRP rod in terms of the ultimate loads, the energy dissipation, the ductility index, and Plastic hinge formation, which was around 34% improvement for ultimate loads, 6.61% increasing in energy dissipation, and 1.12 for ductility. Besides, frames reinforced with CFRP bars showed different behaviour than frames reinforced with GFRP bars due to the low elastic modulus of GFRP bars, which was increased dramatically the deflection. Comparisons between the two numerical software results showed slightly different between them. Also, verifying the numerical results with previous experimental results confirmed the accuracy of the finite elements models.

1. Introduction

In the recent past, the use of fibre reinforced polymers (FRP) for retrofitting and strengthening has increased and become a valid option. FRP has turned out to be an excellent strengthening material for repair and strength of RC structures contrasted more than other customary strengthening materials. There is a various form of Fibre Reinforced Polymer (FRP) such as sheets, plates, cables, and lately, in bar form. The use of CFRP and GFRP rod to avoid unpredictable and brittle failures due to lack of strength in RC parts, strengthening techniques based on the use of fibre reinforced polymer (FRP) materials have been proposed and developed to become widespread practice over recent years. El-Amoury and Ghobarah (2002) Studied on Seismic rehabilitation of beam-column joint using GFRP sheets [1]. They found that the using GFRP jacketing controlled the concrete integrity by confinement and improved the ductility and the load-carrying capacity of the rehabilitated joint. The joint rehabilitation eliminated the brittle joint shear failure, increased the energy dissipated by the specimen and reduced the stiffness degradation of the joint. Also, by trying improve the seismic strength and performance of reinforced concrete exterior beam–column joints Ha et al. (2013) used embedded (CFRP) bars combined with CFRP sheets [2]. They found that the use of the embedded CFRP hexagonal bars combined with externally bonded CFRP sheets minimizes flexural cracks and damage
of concrete near the joint. Burningham et al. (2015) investigated on repairing method for RC deep beams with external unbonded post-tensioned (CFRP) rods [3]. They found that the deflection capacity remained the same for both repaired beams and control beam, but the ultimate load capacity was increased of the repaired beams. The repaired beams had an ultimate load capacity 1.25 to 1.27 times the capacity of the control beam. An experimental program for RC T-cross section beams strengthened in shear using the Embedded Through-Section (ETS) steel bars technique and ETS CFRP rods has been done by Breveglieri et al. (2015) the CFRP bars provided higher shear strengthening effectiveness than steel bars, due to the larger ultimate force capable of being mobilized in inclined bars [4]. Also, a significant increase of load carrying capacity was obtained by using the proposed technique. Capozucca and Bossoletti (2015) presented an experimental and theoretical analysis of concrete beams with NSM CFRP rectangular rods. The beams appear a higher capacity with reduction of deflection and increase of stiffness [5]. Saqan et al. (2017) studied the seismic performance of rigid frames strengthened with externally bonded CFRP fabric and near-surface mounted (NSM) CFRP bars [6]. Both strengthening technologies improved the behaviour compared to the control specimen. The specimen with NSM bars out-performed its counterpart in yielding strength and ultimate strength. The effects of the FRP bars on the seismic performance of the columns has been studied by Cai et al. (2017) results showed that adding additional CFRP bars into the conventional steel reinforced concrete (SRC) columns was efficient in improving the post-yield stiffness ratios and mitigating the residual displacements, while the hysteretic energy dissipation could be maintained [7].

From the previous research that focused on strengthening RC frames, beam, column and joints by various methods of strengthening, it can be concluded that the ordinary reinforced concrete frame has low resistance to seismic loading as this kind of building have a lack of lateral loading resistance. Application of using FRP rod as the main reinforcement is still rarely used in many areas, especially in the strengthening of the Structure. Also, previous techniques that have been developed for strengthening RC frame is inadequate for preventing the seismic effect. Thus, this study is aimed to investigate the behavior of RC frame with replacing FRP rod instead of steel rebars.

2. Consider Model
In the present work in order to evaluate the effect of application of CFRP rod in reinforce concrete frame, the tested RC model by Lu et al. (2008) is considered figure 1. The size and dimension details of the multi-story frame (beam, column, slab and foundation) showed in figure 2 [8].

![Figure 1. Frame structure formed by Lu et al. (2008)](image-url)
Figure 2. The dimension for beam and column of the frame model

The position of CFRP rod and GFRP rod is in the joint of frame with 50% CFRP rod and 50% GFRP rod as show in Figure 3.

Figure 3. The position of the steel and FRP rod.

3. Finite Element Model
The parametric study was conducted to develop finite element models of RC frame with embedded FRP rod subjected to dynamic loading using ABAQUS and ARCS3D finite element software’s to evaluate the effect of embedded FRP rod in seismic response of frame building.

3.1. ABAQUS Model
Five frames were modelled as; the first frame is the bare frame that modelled base on Lu et al. (2008) research [8]. The second model was the frame with 100% embedded CFRP rod, its mean that all the steel rebars in beams and columns is changed to CFRP rod, and the same thing for the third model that was frame with 100% embedded GFRP rod which replaced all the steel rebars in beams and columns with GFRP rod. The dimensions of beams, columns and the foundation are same to bare frame model. Another two frames are a frame with 50% CFRP rod and 50% GFRP rod. In these two frames, half of the steel rebars will replace with CFRP rod and GFRP rod, respectively.
For the five frames modelled by ABAQUS software, the mechanical properties of the normal strength concrete that used in this study are defined as concrete grade B50. The elastic and plastic behavior of the concrete material is modelled base on concrete damage plasticity (CDP) thorium and the material parameters base on Jankowiak and Lodygowski (2005) research [9]. For each frame models, the mechanical properties of reinforcing bars and shear links of steel are defined same. The mass density of steel is 7850 kg/m^3, Young’s modulus 210000N/mm^2, Poisson’s ratio 0.3, and the maximum Yield stress 470. The properties of FRP rod are listed in tables1 below base on Elsayed et al. (2015) [10]. Table 1 show the properties of FRP rod.

Table 1. Properties of FRP rod

| FRP type | Diameter(mm) | Density kg/m^3 | Ultimate Tensile Strength (MPa) | Tensile Young’s modulus(GPa) | Poisson’s ratio |
|----------|--------------|----------------|---------------------------------|----------------------------|----------------|
| CFRP     | 13           | 1650           | 2079                            | 138                        | 0.26           |
| GFRP     | 13           | 2170           | 716                             | 44.3                       | 0.2            |

Once the entire parts of the specimen have been assigned to their relevant properties, the instance part is then being imported into the assembly module to assemble the parts. The model assembly of the 3D multi story frame showed in figure 4 below.

Figure 4. Overall assembly of model parts

In this study, the interaction that has been used to link reinforcement (steel and FRP rod) with concrete was embedded region and tie connection between beams and columns. All frames where meshed with 300 mm elements as shown in figure 5.
The type of boundary condition for all degree of freedom is defined as a fixed boundary condition at the bottom of the foundation (\(U_1=U_2=U_3=UR_1=UR_2=UR_3=0\)). That’s mean that the movement in all direction will be restricted. The load is applied as uniform displacement load to the top of the frame in X-Direction (\(U_1=1\)). Figure 6 shows the boundary condition and load location for the model. The amplitude of displacement applied was 200 mm by Jabbar et al. (2016) as show in figure 7 [11].
3.2. ARCS3D models

The new computer program that has been developed by University Putra Malaysia to use in many structural seismic simulations called ARCS3D had been used in this study. Three frames model were considered and designed by this software. These models were, bare frame, frame with 100% embedded CFRP rod and frame with 100% embedded GFRP frame.

The properties of the material that have been used in this study were the properties that have been used in ABAQUS models base on Lu et al. (2008) research [8]. Same size and dimensions of beams, columns and same section properties. The section properties of reinforced concrete beam and column in bare frame are shown in Figure 8.
For the CFRP rod frame, the section properties of beam and column are shown in Figure 9. Also, figure 10 shows the section properties for GFRP rod frame.
3.3. Time history analysis

Time-history analyses used to estimate the structural stability against earthquake. The analysis result obtained under the three-dimensional El Centro earthquake excitation as shown in figure 11.
Figure 11. Earthquake acceleration record components of El Centro. (a) North–south component, (b) east–west component, (c) up–down component.

X-direction will represent North-South component, Z direction will represent East-West component, and Y direction will represent Up-Down component. Figure 12 shows the input data of in ARCS3D software. The models consist of 24 nodes, 21 beam elements and 18 column elements as it is shown in Figure 13.
3.4. Pushover analysis

In this study, different analyses were conducted in order to fulfillment that aims of this study. Pushover test was conducted to get the maximum force-displacement for each frame. The pushover test analysis stats when it has been applied initial force on the top nodes in the Z direction. However, several steps should be done before clicking on the run for the non-linear static analysis, starting from input number of iterations in each analysis, which is 8, 0.01 for convergence tolerance and the load.
steps number were 39. Furthermore, the total time requires to do the analysis is 1.2 second. After that, it has chosen the nodes to apply the increment load and the node that it wants to observe the displacement and how much is the force stand in need before the modules callups withdraw the charts for force displacement. Figure 14 shows the steps of pushover test.

![Image of pushover test steps](image1)

- a. Select the node for apply increment load
- b. Select node for getting the results

**Figure 14.** The steps of pushover test.

### 4. Results and Discussion

This study has been done by two finite elements software. The first part describes the results of the modelling testing by ABAQUS software: The dynamic performance of each model was evaluated by the applied cyclic load on the top of frames to study the behavior in relation to Energy Dissipation, displacement, strength reduction, ductility, stresses, and strain.

The second part will describe the results of verifications by ARCS3D software by comparing the cyclic loading results from ABAQUS software with the results of pushover test from ARCS3D software. then, compare between the experimental test that has been done by Lu et al. (2008) [8] and Hejazi et al. (2016), Hejazi et al., 2009 Abdi et al. (2015) with the numerical result.[12-14]

#### 4.1. ABAQUS software

**4.1.1. Frames subjected to cyclic loading.** This part will present the output of the ABAQUS FE models analysis in order to evaluate the effect of embedded FRP rod on reinforcing concrete frame subjected to dynamic loading; all considered models were subjected to cyclic displacement. Five different models were simulated based on actual specimen. The load-displacement curve, stresses and strain will be discussed in this section.

The hysteresis analysis for the cyclic loading of the bare frame, frame with embedded 100% CFRP rod, frame with embedded 50% CFRP rod, frame with embedded 100% GFRP rod, and frame with embedded 50% GFRP rod is presented in Figure 15. A marked difference was indicated between the load-deflection curves of the frames with embedded CFRP rod and frames with embedded GFRP rod compared with a bare frame. Also, there is slightly different between frames with embedded 100% FRP rod and frames with embedded 50% FRP rod. In another hand, the hysteresis analysis for the cyclic loading for a frame with embedded CFRP rod was bigger than frame with embedded GFRP rod.
The ultimate load for bare frame was about 65.8 KN and for frame with embedded 100% CFRP rod, frame with embedded 50% CFRP rod was 87 and 88.2 KN, respectively, indicating a 32, 34%, respectively increasing in ultimate load. Meanwhile, the maximum load of frame with embedded 100% GFRP rod, frame with embedded 50% GFRP rod was 67.1 and 69.2 KN, respectively, indicating around 2 %, 5.1 % respectively increase in ultimate load comparing with bare frame with same displacement. This is because of high tensile strength of CFRP rod, which was increased dramatically the lateral strength comparing with GFRP rod and steel rebars.

The energy dissipation for CFRP rod frames was increased by 5.96 % and 6.61% indicating a noticeable growth in beam performance. Meanwhile, the energy dissipation for all GFRP rod frames was substantially reduced by 17.34 % and 15.70 %, indicating a noticeable deduction in frames performance. The ductility of the bare frame was 1.08, whereas that of the frame with embedded 100% CFRP rod, frame with embedded 50% CFRP rod, frame with embedded 100% GFRP rod, and frame with embedded 50% GFRP rod was about 1.11, 1.12, 1.09, 1.11, respectively. Table 2 presents a comparison of the ultimate load capacity resulting from cyclic analysis for different frames.
Table 2. Frames under cyclic load.

| Frame         | Load (KN) | Reduction (%) | Area       | Increasing (%) | At maximum force (mm) | At 0.85 from maximum load | ductility |
|---------------|-----------|---------------|------------|----------------|------------------------|---------------------------|-----------|
| Bare frame    | 65.8      | -             | 78495021.8 | -              | 126                    | 117                       | 1.08      |
| 100% CFRP rod | 87        | 32            | 83170838.05| 5.96           | 126                    | 114                       | 1.11      |
| 50% CFRP rod  | 88.2      | 34            | 83682378.45| 6.61           | 126                    | 113                       | 1.12      |
| 100% GFRP rod | 67.1      | 2             | 64884325.16| -17.34         | 126                    | 116                       | 1.09      |
| 50% GFRP rod  | 69.2      | 5.1           | 66168628.41| -15.70         | 126                    | 114                       | 1.11      |

4.1.2. Comparison between stress, strain and damage for different frames. This section summarizing the stresses, strain and state of damage for bare frame, frame with (50-100) % embedded CFRP rod and frame with (50-100) % embedded GFRP rod. As mentioned earlier, the majority of the stresses happened in the beam-column joint for all of the frames because beam column joints in a reinforced concrete moment resisting frame are crucial zones for transfer of loads effectively between the connecting elements (i.e., beams and columns) in the structure especially during many earthquakes has demonstrated heavy distress due to shear in the joints that culminated in the collapse of the structure as show in figure16.
Due to this huge stress concentrate in beam-column joints, the strain of the frames will be higher in the joints of the frames more than the other parts as show in figure 17.
Figure 17. Strain in different frames

- a. Bare frame strain
- b. Strain in concrete for frame with 100% CFRP rod
- c. Strain in concrete for frame with 50% CFRP rod
- d. Strain in concrete for frame with 100% GFRP rod
- e. Strain in concrete for frame with 50% GFRP rod
Applying the pull and push by cyclic load test led to damage happening to the foundation of the frames more than the other parts as shown in figure 18.

a. Damage in bare frame

b. Damage in concrete for frame with 100% CFRP rod

c. Damage in concrete for frame with 50% CFRP rod

d. Damage in concrete for frame with 100% GFRP rod
e. Damage in concrete for frame with 50% GFRP rod

Figure 18. Damage in different frames

The flexibility of the FRP rod play a pig role in the stiffness of the RC frames and that affected negatively in the stresses and strain of the concrete. Table 3 show the stresses, strain and damage for different frame. It is show that the stress of the concrete was increased in the frames with FRP rod around 4% comparing with bare frame because the low value of elastic modulus of the FRP rod materials. And simultaneously, the strain and damage of the frames increased by 41% and 94% respectively, due to the increase of stresses of the frame with FRP rod.

Table 3. Stresses, strain and damage for different frame

| Frame                | Stress (MPa) | Increase% | Strain | Increase% | Damage | Increase% |
|----------------------|--------------|-----------|--------|-----------|--------|-----------|
| Bare frame           | 46.06        | -         | 0.018  | -         | 0.029  | -         |
| Frame with 100% CFPR rod | 47.53        | 3.19      | 0.026  | 41.38     | 0.047  | 60.03     |
| Frame with 50% CFPR rod | 47.64        | 3.43      | 0.023  | 25.07     | 0.047  | 60.03     |
| Frame with 100% GFRP rod | 47.75        | 3.67      | 0.022  | 19.63     | 0.048  | 63.43     |
| Frame with 50% GFRP rod | 47.86        | 3.91      | 0.026  | 41.38     | 0.057  | 94.08     |

4.2. ARCS3D software

4.2.1. Plastic hinge formation in structural members. After the plastic hinge occurs in a structural member that indicates that elements are failed due to apply large force on the structure exceed the capacity of the members of the structure to prevent this force. Table 4 shows the maximum number of the plastic hinge with increasing the coefficient for ground acceleration until the failure of the
structure. It can be noticed that the coefficient of ground acceleration of the bare frame can increase up to 2 times to collapse with 16 plastic hinges. On the other hand, the coefficient of ground acceleration can be increased up to 2.5 times with 16 plastic hinges for CFRP frame and 2.75 times with 24 plastic hinges for GFRP frame to failure. It means the ability of CFRP and GFRP frame has increased to resist seismic hazard.

Table 4. Number of the plastic hinge

| Coefficient for Ground Acceleration | Bare frame | CFRP frame | GFRP frame |
|-----------------------------------|------------|------------|------------|
| No. of Plastic Hinge              | 1          | 1          | 1          |
| 1                                 | 2          | 0          | 2          |
| 1.25                              | 14         | 0          | 10         |
| 1.5                               | 14         | 2          | 14         |
| 1.75                              | 16         | 2          | 14         |
| 2                                 | Failure (16) | 2          | 14         |
| 2.25                              | 9          | 2.25       | 14         |
| 2.5                               | Failure (16) | 2.5       | 18         |
| 2.75                              | Failure (24) |            |            |

Figure 19 shows the maximum number of the plastic hinge and its location for all type of frame. It shows that the plastic hinge occurred in beam-column connection for all frame and the maximum number was (16, 16, 24) plastic hinge for bare frame, CFRP frame and GFRP frame respectively. To realize earthquake-resistant reinforced concrete structures, columns and beams are necessary to be ductile enough to make sure the structure should not fail in the brittle state under earthquake. FRP material described as it is more flexible than steel. Therefore, it shows more flexible behavior in the concrete frame, giving more ductility for concrete beams and columns to deal with seismic hazards and prevent it as much as the concrete able to stay without collapsing. Thus, it can be noted that the frames with CFRP and GFRP rod resist a higher degree of earthquakes. At the same time, the number of plastic hinges will increase as a result of low in elastic modulus of FRP material.
5. Comparison between ABAQUS and ARCS3D software results

In this section, pushover test conducted to determine the maximum force that can apply to get the maximum displacement at the top of the third floor for bare frame, 100% CFRP frame and 100% GFRP frame. The test conducted by finite element software ARCS3D to compare with the results from ABAQUS. Figure 20 clarify pushover test for bare frame, CFRP frame and GFRP frame.

**Figure 19.** Plastic hinge in Bare frame, CFRP frame and GFRP frame

**Figure 20a.** Pushover test for the bare frame by ABAQUS and ARCS3D.
Figure 20b. Pushover test for the CFRP frame by ABAQUS and ARCS3D.

Figure 20c. Pushover test for the GFRP frame by ABAQUS and ARCS3D.

Figure 20. Pushover tests for bare frame, CFRP frame and GFRP frame by ABAQUS and ARCS3D.

Table 5 shows the difference between results from ARCS3D and ABAQUS software for different frames. It shows that there is no much different between both of them.

Table 5. The difference between results from ARCS3D and ABAQUS software’s

| Frame      | Bare Frame | CFRP Frame | GFRP Frame |
|------------|------------|------------|------------|
|            | Force (kN) | Displacement (mm) | Force (kN) | Displacement (mm) | Force (kN) | Displacement (mm) |
| ABAQUS     | 65.858     | 126        | 87         | 126            | 67.13      | 126                 |
| ARCS3D     | 60.95      | 125.243    | 85.36      | 127.31         | 65.835     | 125.5828            |
| The difference % | 8.05 | 0.60 | 1.92 | -1.03 | 1.97 | 0.33 |

6. Validation of FE with ARCS3D
In order to find out the lateral displacement of the structural element that occurs due to a significant force this causes damage or collapse for members. The time history analysis was conducted by ARCS3D software by apply 1940 El Centro earthquake waves to obtain the displacements in the horizontal direction for the bare frame as show in figure 21.
Figure 21. Displacement for each floor of bare frame

a. Third floor Displacement=11.51 mm

b. Second floor Displacement= 8.4 mm

c. First floor Displacement= 3.5 mm
Figure 22 illustrates that the results of the numerical analysis in X-Direction at the top of the third story was 11.51 mm. Comparing with the results obtained by Hejazi et al. (2016) and Lu et al. (2008) that showed that the maximum displacement in the X-Direction was 12.2 mm. [14, 8]

![Displacement Response (mm)](image1)

Lu et al. (2008)

![Displacement Response (mm)](image2)

Hejazi et al. (2016)

![Displacement Response (mm)](image3)

Present study

**Figure 22.** Time history analysis for the bare frame in X-Direction

7. Conclusion
In this study, the seismic performance of multi-story RC frames were analytically investigated and determined by conducting non-linear finite elements analysis using ABAQUS and ARCS3D software. The overall objective of this study analytically investigated and compares with an experimental study that has been done by Hejazi et al. (2016) subjected to dynamic loading [14]. More specifically, the objective was to study and evaluate the structural integrity in terms of lateral strength, displacement, ductility, number of plastic hinges, damage behaviour of concrete and energy dissipation for each frame under cyclic loading by ABAQUS software then verify and compare with time history and pushover test by ARCS3D software. Base on the results that obtained from analytical analysis, the following points can be concluded:

1. Base on cyclic loading analysis by ABAQUS, the hysteresis graph shows that the frames with CFRP rod have the best performance among other cases. GFRP rod frames have slightly different from a bare frame. Energy Dissipation of GFRP frames are less than the bare frame. The Energy Dissipation for CFRP frame improved by 6.61% and 5.96 % for a frame with 50% CFRP rod and frame with 100% CFRP rod comparing with a bare frame. The ductility for CFRP frames and GFRP frames were improved compared with a bare frame.
2. Pushover test by ARCS3D: it's showed similar results with cyclic loading test, where the CFRP rod frame has the higher ultimate strength compared with GFRP rod frame and bare frame. Also, the ultimate strength of GFRP frame was more than bare frame.
3. in terms of number of plastic hinge, GFRP frame has the higher number of plastic hinge (24) with the higher coefficient of ground acceleration (2.75) then the CFRP frame with (16) plastic hinge with (2.5) coefficient of ground acceleration. The worse condition with the bare frame, the number of plastic hinge was (16) at the coefficient of ground acceleration (2).

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