

Studying The Seismic Behavior of FRP (Fiber Reinforced Plastic) Pipe in Hybrid Reinforced Concrete Column Using the Finite Element Method

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Abstract

Nowadays, reinforcement is an inevitable and rational thing to ensure the safety of structures. The use of FRP is one of the methods of reinforcing reinforced concrete buildings against lateral loads (earthquake). Columns, as the most important part of the structure, are of great importance in providing the strength, stability and ductility of the structure. Increasing the ductility and compressive strength of reinforced concrete columns is one of the notable effects of confining concrete, which is mostly done in three ways: using a steel jacket, a concrete jacket, and polymer fibers (FRP). Hybrid columns are used to increase confinement, increase flexibility, increase shear strength in the column, and consequently increase the efficiency of the member. Therefore, strengthening reinforced concrete columns with FRP has been used in many cases to increase the confinement of concrete and also to increase the ductility of the structure. Due to the importance of the degree of flexibility and energy absorption capacity in structures, especially under the influence of lateral loads, methods should be sought that increase the ductility of concrete structures. By controlling the lateral expansion of concrete by enclosing it, the strength and flexibility of concrete can be significantly increased. The use of FRP fibers for reinforcing concrete columns is an effective method for strengthening damaged concrete columns, as it enhances both load-carrying capacity and energy dissipation. The numerical results showed that the GFRP-confined model exhibited approximately 15% higher energy dissipation compared to the steel-confined model, demonstrating its superior ability to absorb seismic energy and reduce structural damage.

This study aims to numerically investigate the seismic response of hybrid RC columns confined with FRP tubes under different ground motions using FEM in ABAQUS

Keywords: Hybrid reinforced concrete column; Finite element analysis; Seismic behaviour; bending moment; Strength; ABAQUS;

1. Introduction

Reinforced concrete (RC) columns are the primary load-bearing members in structural systems, and their seismic performance plays a critical role in ensuring structural safety. Under earthquake loading, RC columns may experience brittle failure, premature buckling, and limited ductility, leading to severe structural damage [1], [2]. Conventional strengthening techniques offer partial improvements; however, the need for advanced and durable solutions has promoted the use of fiber-reinforced polymer (FRP) composites to enhance confinement efficiency, stiffness, and energy dissipation capacity [3].

Concrete-filled FRP tubes (CFFTs) have emerged as an effective strengthening system, providing continuous confinement to the concrete core and improved seismic resistance compared with traditional RC columns [4]-[6]. Experimental and analytical studies have demonstrated that FRP confinement can delay local buckling and significantly improve ductility and post-yield behavior under cyclic loading [7]-[9]. In particular, hybrid FRP-concrete-steel columns have shown superior displacement capacity and energy dissipation when compared to conventional RC members [10],[11].

However, few studies have examined the combined effect of FRP confinement and steel reinforcement interaction under cyclic seismic loading, particularly with respect to buckling stability, flexural stiffness, and rotational ductility. Most existing research has focused on isolated confinement effects or compressive behavior, while the integrated seismic response of hybrid FRP-RC columns remains insufficiently understood [12], [13]. This gap limits the ability to fully assess the effectiveness of FRP tubes in enhancing the overall seismic performance of RC columns.

To address this gap, numerical modeling using the finite element method (FEM) provides an efficient and reliable approach for capturing nonlinear material behavior, confinement effects, and cyclic degradation mechanisms that are difficult to observe experimentally. While laboratory testing is often constrained by cost and practical limitations, FEM enables detailed investigation of stress redistribution, buckling behavior, and interaction between concrete, steel reinforcement, and FRP confinement under different ground motion records.

Accordingly, the present study employs FEM to investigate the seismic performance of hybrid reinforced concrete columns confined with FRP tubes under cyclic loading. The analysis focuses on the interaction between FRP confinement and steel reinforcement, with particular emphasis on buckling stability, flexural stiffness, and rotational capacity. The findings are expected to provide valuable insights into the seismic behavior of hybrid FRP-RC columns and to support the development of improved design recommendations.

2. Research goal and innovations

The novelty of this study lies in the comparative FEM-based evaluation of the seismic behavior of hybrid RC columns confined with GFRP, CFRP, and steel jackets, with a specific focus on displacement response, load-carrying capacity, and energy dissipation under realistic Iranian design earthquakes (Bam, Tabas, and Manjil).

Unlike previous studies that primarily examined single confinement techniques or focused on compressive behavior under simplified loading conditions, this research offers a unified and systematic comparison of multiple confinement systems within the same numerical framework and seismic context. Furthermore, the use of representative Iranian ground motion records provides a region-specific perspective that has not been sufficiently addressed in earlier investigations. This integrated approach enables a clearer understanding of the relative efficiency of FRP and steel jacketing systems in enhancing the seismic resilience of RC column.

3. Modeling of samples

3.1. Modeling geometry

In this analysis, hybrid reinforced concrete columns are modeled using a 10 mm thick steel jacket and 1 mm thick CFRP and GFRP jackets. Several models were considered in this study, including a short hybrid column strengthened with steel, CFRP, and GFRP jackets, as well as a longer column with the same jacket configurations.

The finite element model was discretized using eight-node three-dimensional solid elements with reduced integration (C3D8R). A uniform mesh with an average element size of 0.47 was adopted for all solid parts. The selected mesh density was found to provide a reasonable balance between computational efficiency and result accuracy.

3.2. Defining the characteristics of the materials used in the simulated model

In this section, the properties of the materials used in the research are presented. The mechanical characteristics of steel reinforcement, concrete, CFRP, and GFRP adopted in the numerical simulations are summarized in Table 1.

Table 1. characteristics of materials

| | Mass density kg/m ³ | Modulus of elasticity (GPa) | Poisson's ratio |
|---|-----------------------------------|--------------------------------|--------------------|
| Mechanical characteristics of steel rebar materials | 7850 | 200 | 0.3 |
| Concrete specifications in ABAQUS | 2400 | 26.5 | 0.18 |
| CFRP specification in ABAQUS | 1580 | 21.8 | 0.17 |
| GFRP specification in ABAQUS | 2000 | 62 | 0.22 |

3.3. Loading and boundary conditions

To obtain earthquake acceleration records, ground motion data were extracted from the PEER Strong Motion Database. First, the desired earthquake records were downloaded, and the horizontal acceleration components were separated and saved in text format before being imported into EXCEL software. The input data consisted of raw horizontal acceleration data.

In SEISMO Signal software (version 4), the peak ground acceleration (PGA) corresponding to each record was identified, and the selected earthquake motions were scaled according to the requirements of the Iranian seismic design code (Standard 2800) before being applied in ABAQUS. According to this standard, the acceleration records were scaled such that their response spectra were equal to or greater than the design spectrum within the target frequency range.

For performing nonlinear time-history analysis, earthquake records were selected in compliance with the provisions of Standard 2800 and used after spectral matching with the standard design spectrum. The lateral seismic loads corresponding to the Bam, Tabas, and Manjil earthquakes were applied at the base of the structure in the X-direction, while the base of the column was fully constrained to represent the support conditions.

3.4. Model Validation

Due to the unavailability of experimental data for the investigated configuration, the proposed numerical model was validated against a previously published numerical–experimental study. The comparison demonstrated a close agreement in the overall structural response, indicating that the modeling approach adopted in this study is capable of capturing the essential behavior of the system.

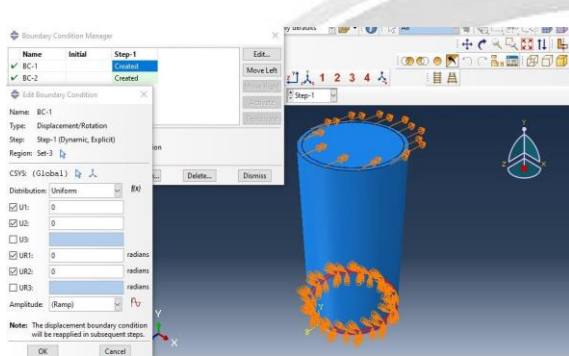


Figure 1. Assignment of loading in CFRP tube in a hybrid reinforced concrete column

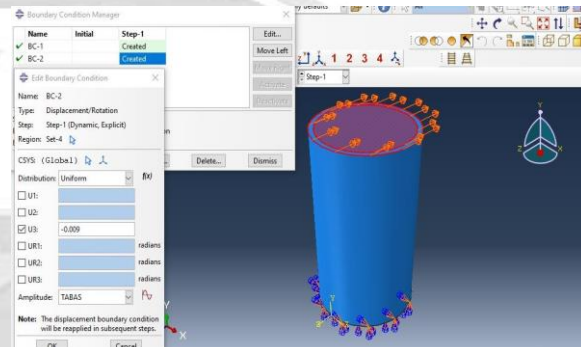


Figure 2. Assignment of loading in GFRP tube in a hybrid reinforced concrete column

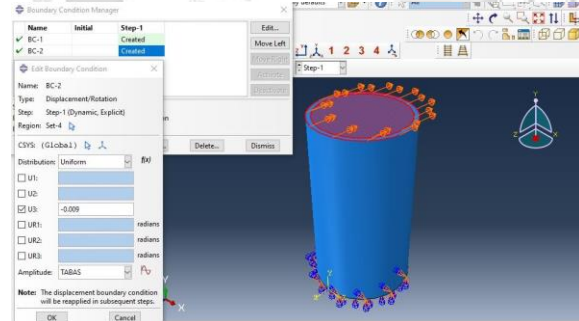


Figure 3 Allocation of loading in steel tube in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters).

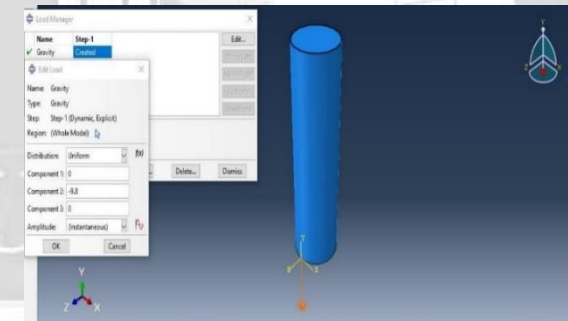


Figure 4. Loading gravity load in Y direction (vertical) in GFRP and CFRP pipe and steel pipe in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters).

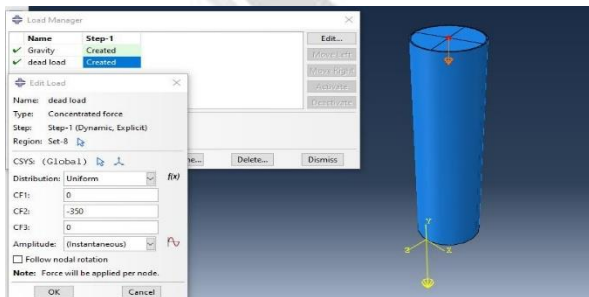


Figure 5 Dead load loading in the Y direction (vertical) in GFRP and CFRP pipe and steel pipe in a hybrid reinforced concrete column

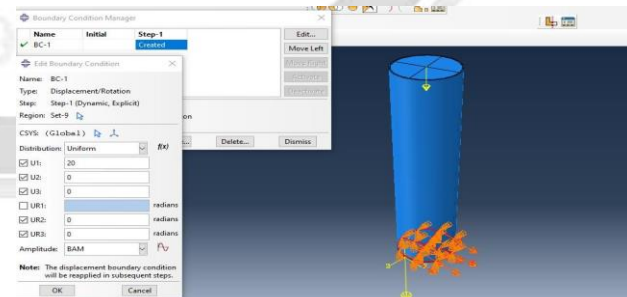


Figure 6. Lateral load loading in the X direction (earthquake) in the vertical direction in GFRP and CFRP pipes in a hybrid reinforced concrete column

4. Presentation of results

The graphs obtained from the analysis of the seismic behavior of a steel pipe, FRP, and GFRP (fiber-reinforced plastic) in a hybrid reinforced concrete column, as well as GFRP, CFRP, and a steel pipe in a hybrid reinforced concrete column with a 40 cm cross section and 3 m height, were generated using the finite element method. The displacement of the roof of the structure under accelerations from different seismic mappings is presented below

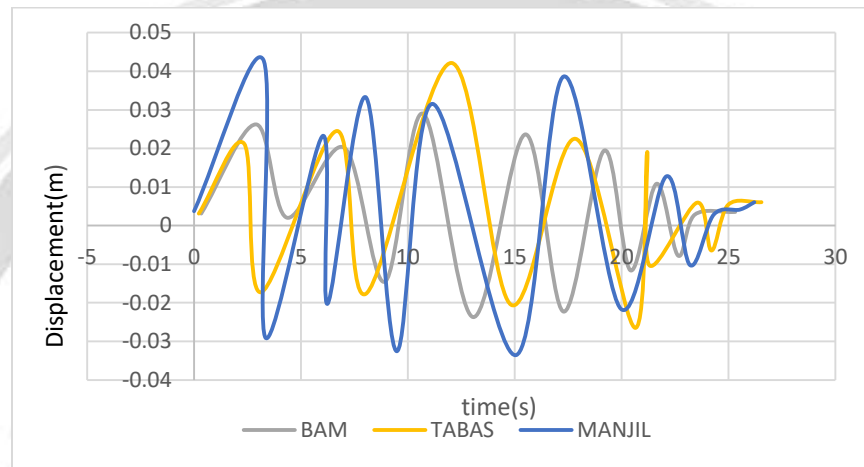


Figure 7. Calculation of displacement of the roof of the FRP tube (Fiber reinforced plastic) in a hybrid reinforced concrete column

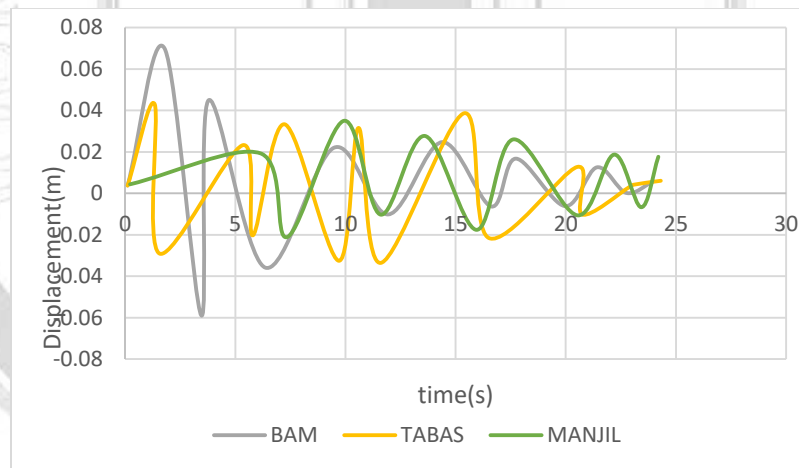


Figure 8. Calculation of displacement of a steel tube roof (Fiber reinforced plastic) in a hybrid reinforced concrete column

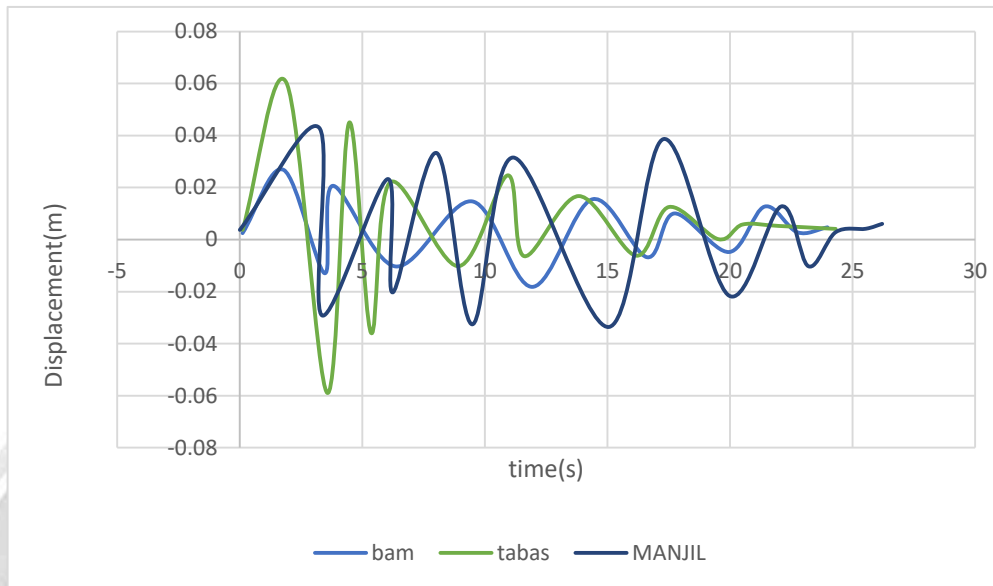


Figure 9: Calculation of the displacement of the roof of the GFRP pipe (fiber reinforced plastic) in a hybrid reinforced concrete column.

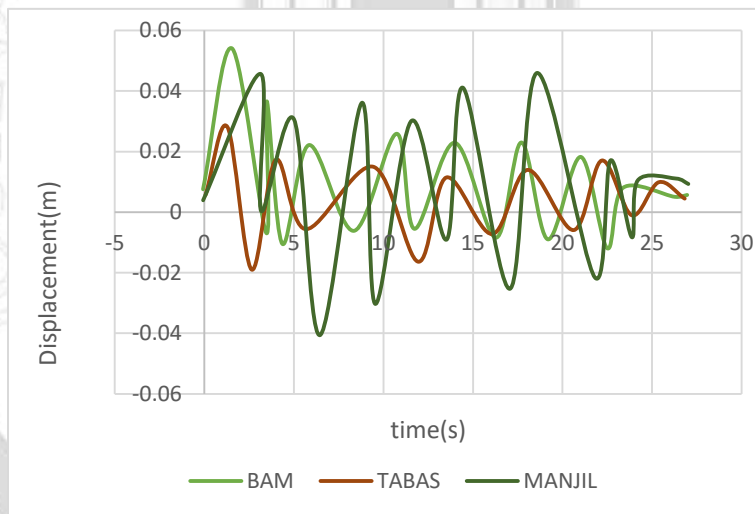


Figure 10: Calculation of the displacement of the roof of the GFRP pipe in a hybrid reinforced concrete column (with a cross-sectional area of 40 cm and a height of 3 m)

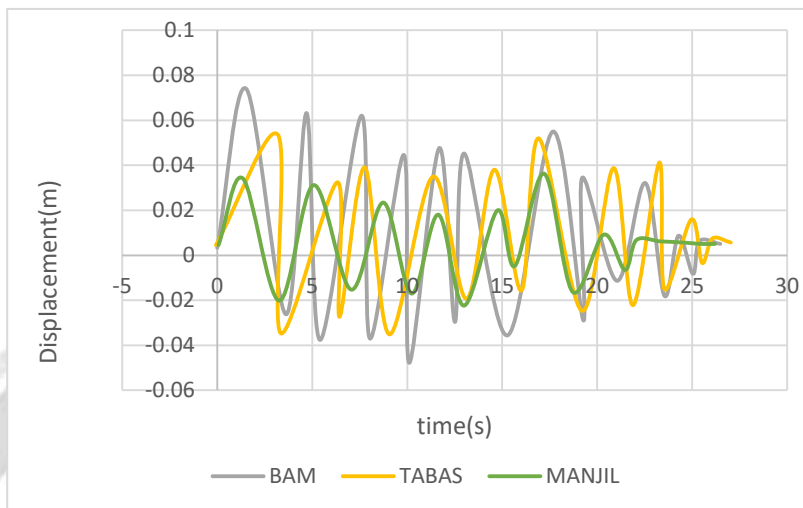


Figure 11: Calculation of the displacement of the roof of the CFRP pipe in a hybrid reinforced concrete column (with a cross-sectional area of 40 cm and a height of 3 m)

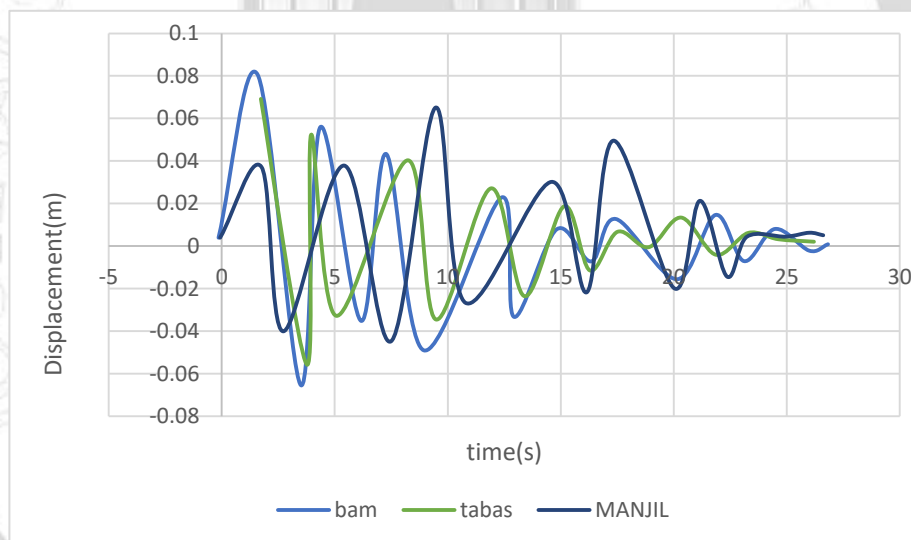
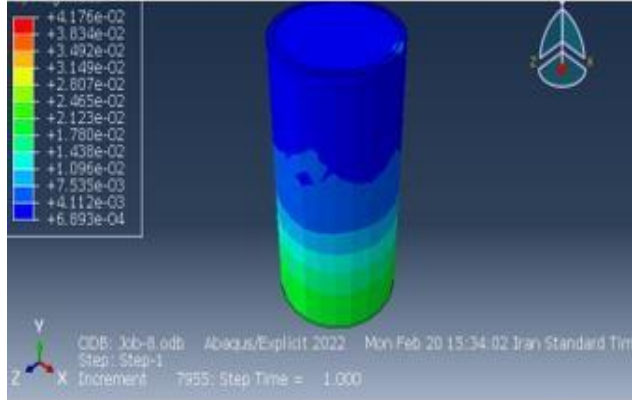


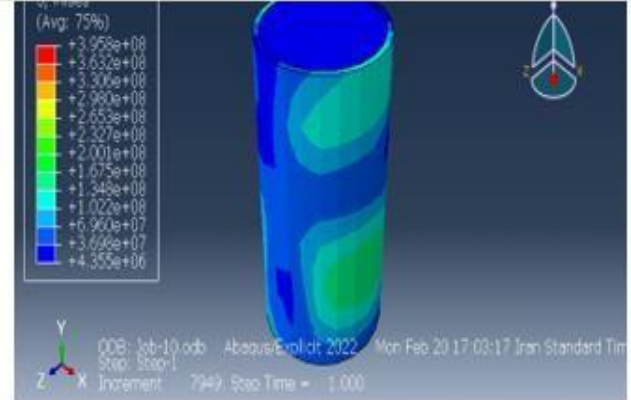
Figure 12 Calculation of the displacement of the roof of the steel pipe in a hybrid reinforced concrete column (with a cross-sectional area of 40 cm and a height of 3 m)

Figures 7 and 8 present the time history displacement response of hybrid reinforced concrete columns confined with GFRP, CFRP, and steel pipes under BAM earthquake excitation. The results show that the GFRP-confined column exhibited the lowest displacement response among all confinement types. Specifically, the maximum displacement of the GFRP-confined column was approximately 20–25% lower than that of the steel-confined column. This improvement is attributed to the higher confinement efficiency and stiffness provided by GFRP, which enhances the structural resistance to seismic loading. Furthermore, increasing the column height to 3 m resulted in increased displacement amplitudes for all confinement types due to increased slenderness effects. These results are consistent with previous studies that

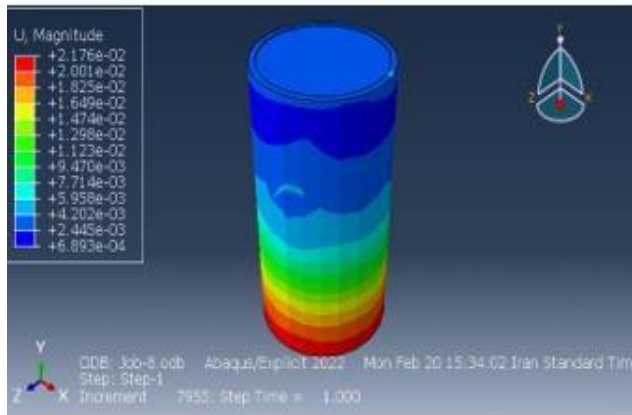
demonstrated the effectiveness of FRP confinement in improving seismic performance and reducing structural deformation.



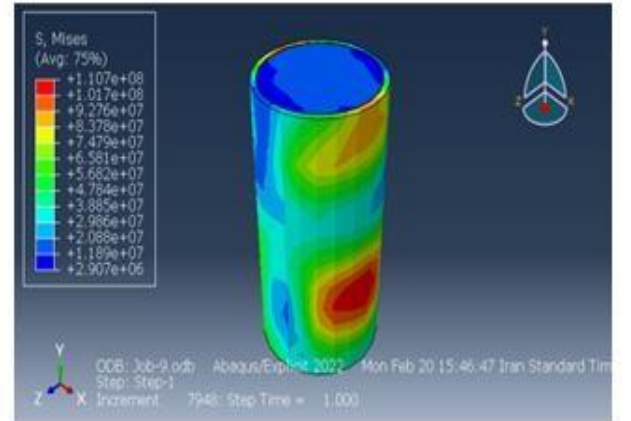
It shows the displacement of the FRP pipe in a hybrid reinforced concrete column under accelerometer (Manjil), the displacement value is 4 cm.



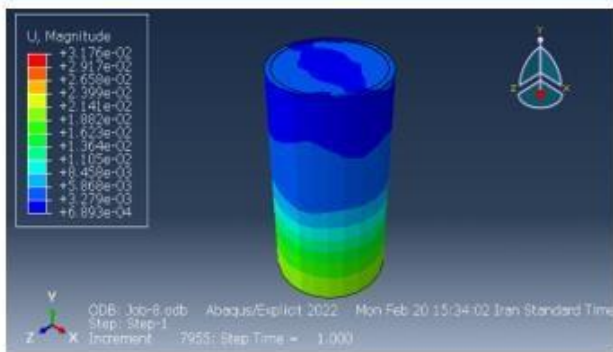
It shows the stress in the FRP pipe in a hybrid reinforced concrete column under acceleration (Manjil), the stress value is 395 MPa.



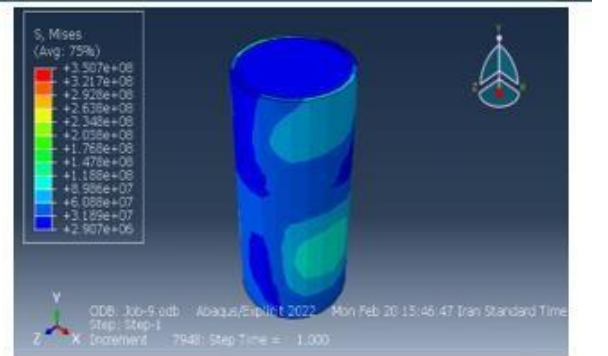
It shows the displacement in the FRP pipe in a hybrid reinforced concrete column under accelerometer (TABS), the amount of displacement is 2.17 cm.



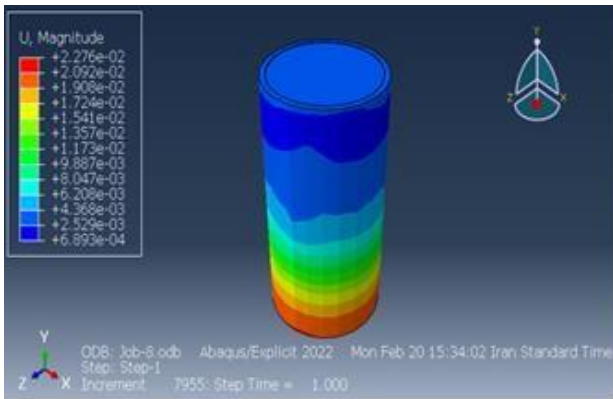
It shows the stress in the FRP pipe in a hybrid reinforced concrete column under accelerometer (TABS), the stress value is 110 MPa.



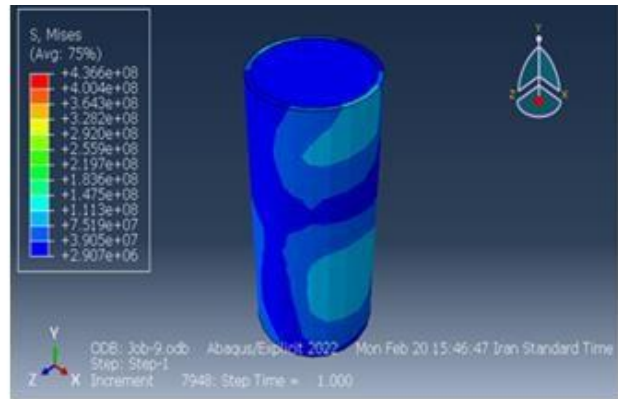
It shows the displacement in the FRP pipe in a hybrid reinforced concrete column under accelerometer (BAM), the amount of displacement is 3.17 cm.



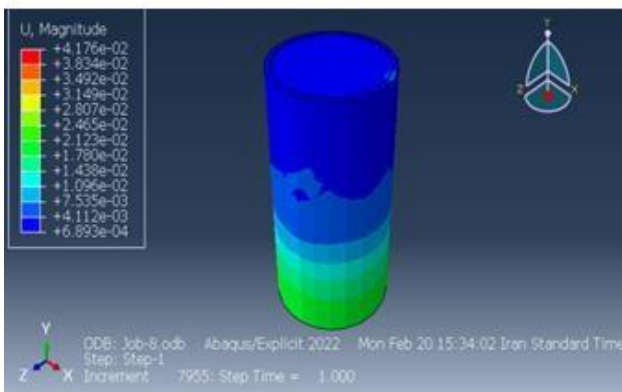
It shows the stress in the FRP pipe in a hybrid reinforced concrete column under acceleration mapping (BAM), the stress value is 350 MPa.



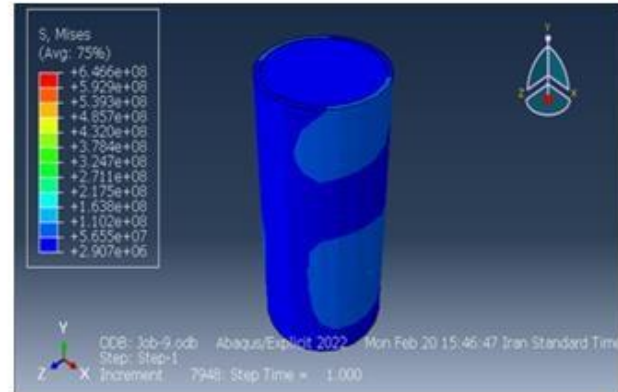
It shows the displacement in the steel pipe in a hybrid reinforced concrete column under accelerometer (Manjil), the amount of displacement is 2.27 cm.



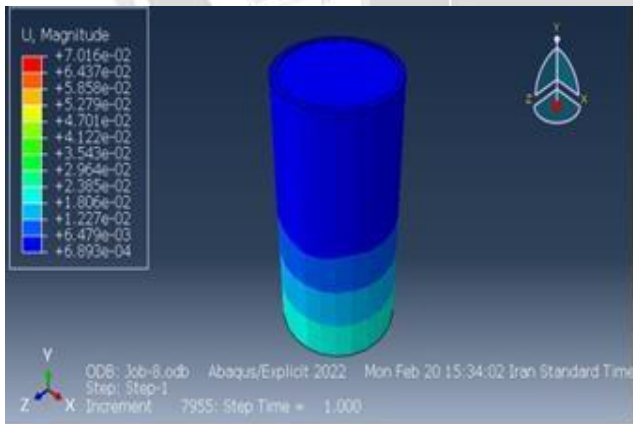
It shows the stress in the steel pipe in a hybrid reinforced concrete column under acceleration (Manjil), the stress value is 436 MPa.



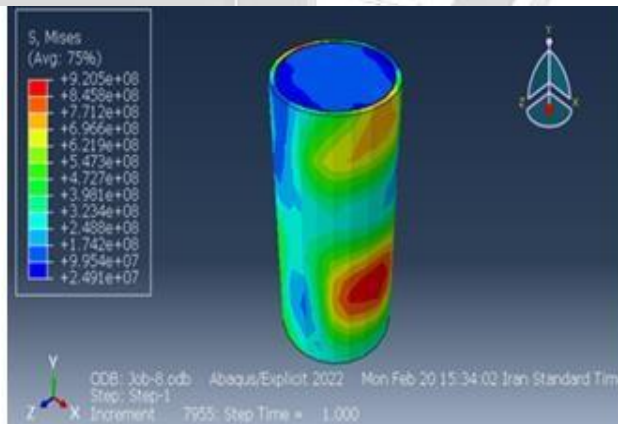
It shows the displacement in the steel tube in a hybrid reinforced concrete column under accelerometer (TABS), the amount of displacement is 4.17 cm.



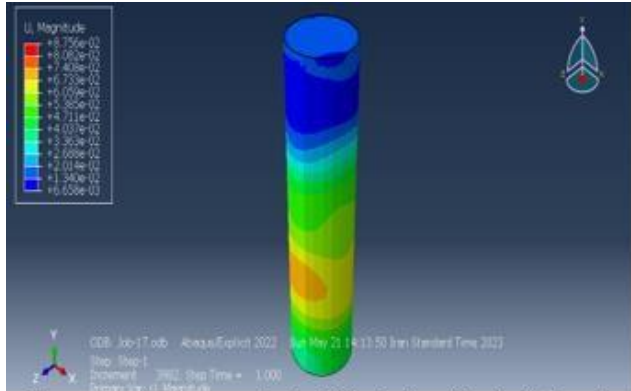
It shows the stress in steel pipe in a hybrid reinforced concrete column under accelerometer (TABS), the stress value is 646 MPa.



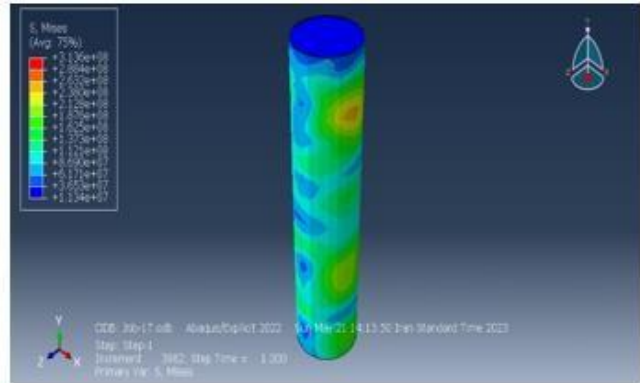
shows the displacement in the steel pipe in a hybrid reinforced concrete column under accelerometer (BAM), the amount of displacement is 7.01 cm.



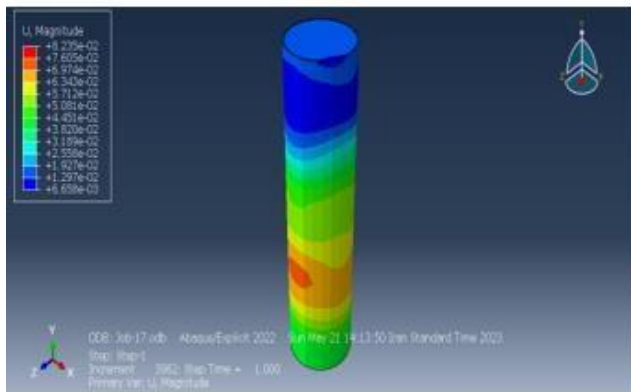
It shows the stress in the steel pipe in a hybrid reinforced concrete column under accelerometer (BAM), the stress value is 920 MPa.



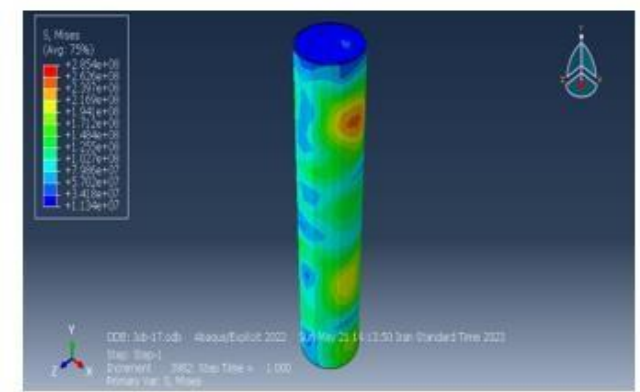
It shows the displacement in the GFRP tube in a hybrid reinforced concrete column under accelerometer (BAM) (with a cross section of 40 cm and a height of 3 meters), the amount of displacement is 8.75



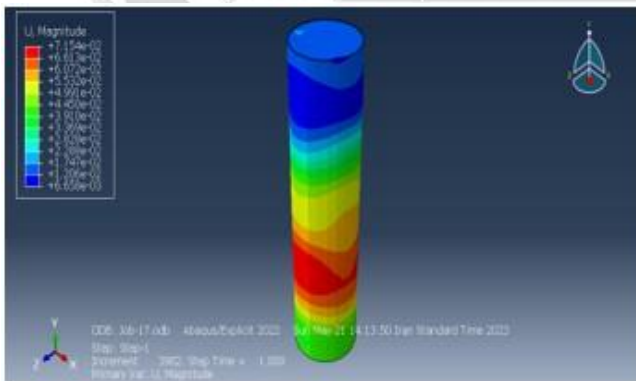
It shows the stress in the GFRP pipe in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters) (BAM), the stress value is 313 MPa.



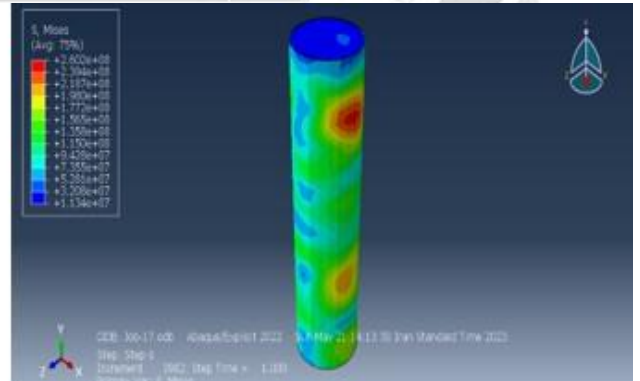
It shows the displacement in the GFRP tube in a hybrid reinforced concrete column under accelerometer (TABS) (with a cross section of 40 cm and a height of 3 meters), the displacement value is 8.23 cm.



It shows the stress in the GFRP pipe in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters) (TABS), the stress value is 285 MPa.



It shows the displacement in the GFRP pipe in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters) (Manij), the amount of displacement is 7.15 cm.



It shows the stress in the GFRP pipe in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters) (Manij), the stress value is 260 MPa.

Table 2: Strength and hardness values (GFRP, CFRP and steel pipes in a hybrid reinforced concrete column).

| Row | Various models | Strength (KN) | Bending moment (N.M) |
|-----|------------------------------------|---------------|----------------------|
| 1 | GFRP pipe under BAM earthquake | 5.30 | 7.45 |
| 2 | GFRP pipe under TABAS earthquake | 5.64 | 7.24 |
| 3 | GFRP pipe under MANJIL earthquake | 5.49 | 6.94 |
| 4 | CFRP pipe under BAM earthquake | 4.94 | 5.91 |
| 5 | CFRP pipe under TABAS earthquake | 4.78 | 5.84 |
| 6 | CFRP pipe under MANJIL earthquake | 4.69 | 5.71 |
| 7 | STEEL pipe under BAM earthquake | 4.59 | 5.66 |
| 8 | STEEL pipe under TABAS earthquake | 4.43 | 5.59 |
| 9 | STEEL pipe under MANJIL earthquake | 4.33 | 5.39 |

Table 3 Strength and Bending moment values (GFRP, CFRP and steel pipes) in a hybrid reinforced concrete column (with a cross section of 40 cm and a height of 3 meters)

| Row | Various models | Strength (KN) | Bending moment (N.M) |
|-----|------------------------------------|---------------|----------------------|
| 1 | GFRP pipe under BAM earthquake | 4.88 | 6.84 |
| 2 | GFRP pipe under TABAS earthquake | 4.9 | 6.25 |
| 3 | GFRP pipe under MANJIL earthquake | 4.95 | 5.95 |
| 4 | CFRP pipe under BAM earthquake | 4.89 | 5.48 |
| 5 | CFRP pipe under TABAS earthquake | 4.4 | 5.12 |
| 6 | CFRP pipe under MANJIL earthquake | 4.3 | 4.85 |
| 7 | STEEL pipe under BAM earthquake | 4.65 | 5.26 |
| 8 | STEEL pipe under TABAS earthquake | 4.21 | 5.02 |
| 9 | STEEL pipe under MANJIL earthquake | 4.11 | 4.67 |

A comparison of the results presented in Tables 2 and 3 reveals the effect of column height on the strength and bending moment of hybrid reinforced concrete columns confined with GFRP, CFRP, and steel pipes under the BAM earthquake.

For the GFRP-confined column, increasing the column height to 3 m resulted in a reduction in strength from 5.30 kN to 4.88 kN, corresponding to a decrease of approximately 7.9%. Similarly, the bending moment decreased from 7.45 N·m to 6.84 N·m, representing a reduction of about 8.2%. This reduction can be attributed to the increased slenderness ratio and reduced lateral stiffness of the longer column, which decreases its resistance to seismic loading despite the confinement provided by the GFRP jacket.

In the case of the CFRP-confined column, the strength showed a slight decrease from 4.94 kN to 4.89 kN, corresponding to a reduction of approximately 1.0%, indicating relatively stable

axial load capacity. However, the bending moment decreased from 5.91 N·m to 5.48 N·m, representing a reduction of approximately 7.3%. This behavior suggests that while CFRP confinement effectively maintains axial strength, the flexural resistance is still influenced by increased column slenderness.

For the steel-confined column, the strength slightly increased from 4.59 kN to 4.65 kN, corresponding to an increase of approximately 1.3%, demonstrating stable axial performance. Nevertheless, the bending moment decreased from 5.66 N·m to 5.26 N·m, representing a reduction of approximately 7.1%, due to reduced lateral stiffness and increased susceptibility to flexural deformation in the longer column.

Overall, all three confinement materials exhibited a decrease in bending moment with increasing column height, confirming the significant influence of column slenderness on flexural performance under seismic loading. Among the materials studied, the GFRP-confined column consistently demonstrated the highest strength and bending moment in both column configurations, followed by CFRP and steel. These results indicate that GFRP confinement provides the most effective enhancement in the seismic performance and load-carrying capacity of hybrid reinforced concrete columns, even with increased column height.

5. Conclusion

The results of the nonlinear finite element analysis demonstrated that FRP confinement significantly enhances the seismic performance of hybrid reinforced concrete columns. Among the investigated confinement materials, the GFRP-confined column exhibited the best overall performance in terms of strength, bending moment capacity, ductility, and energy dissipation.

Specifically, the GFRP-confined model showed approximately 14–23% higher strength and up to 30% higher bending moment compared to the steel-confined column. In addition, the GFRP model showed approximately 15% higher energy dissipation than the steel model, indicating its superior ability to absorb seismic energy and reduce the amount of energy transmitted into the structural core. This improved energy dissipation capacity contributes to enhanced structural stability, increased ductility, and reduced seismic damage.

Furthermore, increasing the column height resulted in a reduction in bending moment capacity for all confinement types due to increased slenderness and reduced lateral stiffness. However, the GFRP-confined column consistently maintained the highest load-carrying capacity and energy dissipation performance compared to CFRP and steel confinement systems.

The finite element analysis results confirm the potential of hybrid FRP–RC systems for improving seismic resilience, structural reliability, and overall performance of reinforced concrete columns under seismic loading. The enhanced confinement provided by FRP materials improves ductility, delays crack propagation, and increases the structural energy dissipation capacity.

Future work should include experimental validation of the numerical results and parametric analysis considering different FRP thicknesses, material properties, and confinement configurations to further evaluate and optimize the performance of hybrid FRP–RC systems.

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دراسة السلوك الزلزالي لأنابيب FRP (البلاستيك المقوى بالألياف) في عمود خرساني مسلح هجين باستخدام طريقة العناصر المحدودة

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الخلاصة

يُعدّ تدعيم المنشآت اليوم ضرورة حتمية ومنطقية لضمان سلامتها. ويُعدّ استخدام الألياف البوليمرية المقواة (FRP) أحد أساليب تدعيم المباني الخرسانية المسلحة ضد الأحمال الجانبية (كالزلازل). وتُعتبر الأعمدة، باعتبارها أهم جزء في المنشأة، ذات أهمية بالغة في توفير القوة والاستقرار والمتانة. ومن أبرز نتائج تدعيم الخرسانة زيادة متانتها ومقاومتها للضغط، ويتم ذلك عادةً بثلاث طرق: استخدام غلاف فولاذي، أو غلاف خرساني، أو ألياف بوليمرية مقواة (FRP). وتُستخدم الأعمدة الهجينة لزيادة التدعيم والمرونة ومقاومة القص في العمود، وبالتالي زيادة كفاءة العنصر الإنشائي. لذلك، يُستخدم تدعيم الأعمدة الخرسانية المسلحة بالألياف البوليمرية المقواة (FRP) في العديد من الحالات لزيادة تدعيم الخرسانة وزيادة متانتها. نظراً لأهمية درجة المرونة وقدرة امتصاص الطاقة في المنشآت، لا سيما تحت تأثير الأحمال الجانبية، ينبغي البحث عن طرق لزيادة مطيلية المنشآت الخرسانية. ومن خلال التحكم في التمدد الجانبي للخرسانة عبر تغليفها، يمكن زيادة مقاومتها ومرونتها بشكل ملحوظ. ويُعدّ استخدام ألياف البوليمر المقوى بالألياف (FRP) لتقوية الأعمدة الخرسانية طريقة فعالة لتقوية الأعمدة الخرسانية المتضررة، حيث يُحسّن كلاً من قدرة تحمل الأحمال وتبديد الطاقة. وقد أظهرت النتائج العددية أن النموذج المُغلف بألياف البوليمر المقوى بالألياف الزجاجية (GFRP) أظهر تبديداً للطاقة أعلى بنسبة 15% تقريباً مقارنةً بالنموذج المُغلف بالفولاذ، مما يبرهن على قدرته الفائقة على امتصاص الطاقة الزلزالية والحد من الأضرار الإنشائية.

تهدف هذه الدراسة إلى دراسة الاستجابة الزلزالية للأعمدة الخرسانية المسلحة الهجينة المُغلفة بأنابيب من ألياف البوليمر المقوى بالألياف (FRP) تحت تأثير حركات أرضية مختلفة باستخدام طريقة العناصر المحدودة (FEM) في برنامج ABAQUS.

الكلمات الدالة: عمود خرساني مسلح هجين؛ تحليل العناصر المحدودة؛ السلوك الزلزالي؛ عزم الانحناء؛ المقاومة؛ برنامج ABAQUS؛