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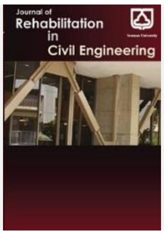

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Numerical Investigation of FRP-Confined Reinforced Concrete Columns Strengthened with Rods Under Cyclic and Monotonic Compression

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ABSTRACT

In this study, a numerical investigation was conducted on the seismic behavior of low-strength reinforced concrete columns, strengthened with steel bars and wrapped with fiberglass tapes and fabrics, using finite element software. The columns were subjected to both monotonic and cyclic loading, and the analysis focused on fracture patterns, failure mechanisms, lateral hysteresis loops, ductility degradation, and stiffness degradation. The results showed that the reference column exhibited brittle shear failure and insufficient ductility. In contrast, the second column, reinforced with steel bars and partially wrapped with fiberglass tapes, demonstrated 30% higher tensile strength compared to the reference column, achieving stable hysteresis loops, improved energy dissipation, and 25% less cracking. The third column, fully wrapped with fiberglass fabric in addition to the steel bars, exhibited 50% higher tensile strength and 75% reduced probability of cracking in the plastic hinge area. These findings underscore the effectiveness of advanced reinforcement techniques in improving the seismic performance of reinforced concrete columns.

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1. Introduction

In recent years, our technical and scientific capabilities have changed due to the continuous development of structural member strengthening methods and researchers have continuously worked on new and better materials to optimize performance and balance cost these reinforcements [1, 2], so many materials have been developed that open new perspectives [3, 4, 5] Polymer fibers are a commonly used composite material and are used in the field of reinforcement, they take many forms (fibers, fabric, strip or braid, etc.) consisting of a set of fine threads that are very resistant to traction and considered as be very strong in relation to their size. In addition to this, polymer fibers have high resistance to chemical compounds and perform well at high temperatures with slight expansion and good corrosion resistance [6, 7]. Polymer fibers are used in civil engineering in many structural engineering applications due to their great advantages and reasonable costs and especially in the reinforcement of reinforced concrete elements [8, 9, 10, 11].

To improve the seismic performance of square reinforced concrete columns, several researchers have investigated basalt and carbon fiber reinforced polymer sheets used as confinement envelopes [12, 13], have studied techniques for reinforcing reinforced concrete elements and have developed new strategies to create elements that are very resistant to collapse and to increase the distortion capacities in order to avoid collapses. New options and techniques have therefore been made available to increase the effectiveness of structural reinforcement systems.

Some research has been conducted to understand the seismic performance of square columns reinforced with FRPs, whereas [14, 15] studied the factors taken into account during reinforcement such as the number of layers and the corner radius for a square column. In addition, other investigations have focused on partial and total confinement strategies [16, 17] .Recent studies have also predicted the compressive strength of CFRP-confined concrete using advanced techniques such as deep learning, which has improved our understanding of the behavior of confined concrete under various conditions [18].

Many methods have also been applied for bonding polymer fiber tapes to the outer surface of the elements to be reinforced, such as some apply the side near-surface mounted (SNSM) method [18, 19] where they made grooves on the sides of the columns, and others apply externally bonded reinforcement (EBR) methods [20, 21]. While recent studies have used GFRP bars or steel bars to stiffen concrete columns to improve shear failure, and to measure stress on stiffeners in specimens, flexural stiffeners capable of withstanding at higher longitudinal forces at yield point have been proposed [22, 23,24] , and new research has focused on machine learning systems for reliably estimating the ultimate condition of FRP-confined concrete, offering an innovative approach to material performance prediction [25].

The study by [26] , was about a new packing and strengthening method, where concrete columns confined by both steel spirals and fiber reinforced polymers (FRP) are presented.

From this point of view comes the hypothesis of the fusion of three methods of reinforcement, where the reinforcement was combined with horizontal steel bars to resist the horizontal loads using the NSM method, which is based on the drilling of grooves in the concrete of the column and the bonding of the reinforcement bars by the epoxy resin, in addition the full wrapping and the partial wrapping by FRP fiber polymers in order to improve the resistance to cyclic loads, such as the first wrapping used by the SNSM method and the second wrap by the EBR method to ensure good adhesion between the FRP layers. Such composite techniques have been shown to significantly improve structural performance, as seen in recent investigations into steel-reinforced polymer composites and grout, which enhance compressive behavior in square concrete columns [27].

In this study, twelve reinforcement schemes were numerically simulated using nonlinear analysis in ABAQUS [28] software to investigate the seismic behavior of columns reinforced by three different strategies. Each strategy was applied under three varying conditions, including the section of rods, the number of layers of fiberglass strips, and the number of layers of fabric. Recent investigations have also explored the use of artificial intelligence techniques for modeling the confined compressive strength of CFRP-jacketed noncircular columns [29], while further advancements have been made by evaluating the load-carrying capacity of beam-column joints using soft computing techniques [30]. These advancements highlight the growing importance of innovative computational methods in the optimization of structural reinforcement strategies.

2. Research significance

This work presents a database of the results of a numerical simulation of a new model for a combination of strategies for reinforcing columns and confining the concrete of these columns, where it was proposed to create grooves in the old concrete and place the strengthening materials in them, such as longitudinal steel bars or fiberglass strips, with the use of epoxy as the adhesive material between the additives and old materials. With this new technology of reinforcement, the structural elements have benefited from high strength to resist stress and improve the behavior of the column while preserving the original space of the element and introducing modern materials with high efficiency and durability, ensuring strong adhesion through the epoxy.
Since the goal of this study is to enhance the seismic performance of concrete columns with low resistance, numerical models for large-dimensional columns and low-resistance CDPM concrete collapse models are proposed. In doing so, the research process has been sped up and the challenges of an expensive experimental program have been eliminated, particularly concerning columns with real dimensions and seismic study.
The overall research process is illustrated in the flow chart shown in Fig. 1. This flow chart provides a visual representation of the sequential steps undertaken during the numerical investigation of FRP-confined reinforced concrete columns, outlining key phases from initial modeling to final analysis.

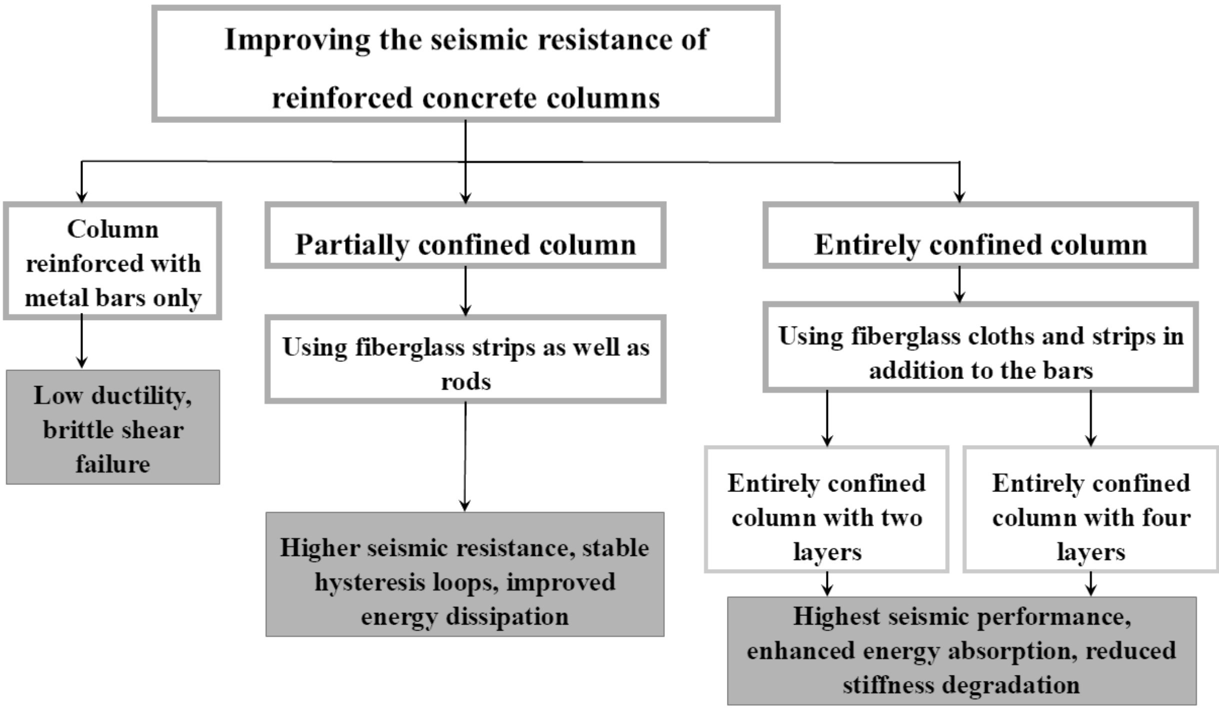


Fig. 1. Flow chart of the research process for FRP-confined reinforced concrete columns.

3. Retrofit considerations

According to previous studies [18, 19] Four different types of failure modes can be observed when seismic loads are applied to reinforced concrete columns, depending on their flexural and shear capacities. The first failure mode is by shear before plasticization of the longitudinal reinforcements, the second is by the flexure-shear failure, The third is the flexural failure and the last mode is the rupture by covering of the longitudinal re-bars in the beams-columns assemblies.
In this paper, the study focuses on the third mode of failure which consists of a rupture by confinement of the region of plastic hinge in bending, which follows the cracking in bending, crushing of the cover concrete, buckling of the longitudinal reinforcements or a rupture. Compression of the concrete core can lead to deterioration of the plastic hinge.
To improve ductility and shear capacity, two strengthening strategies were applied. The first strategy is for the improvement of shear and ductility from the use of longitudinal rebars, and the second strategy for improving displacement ductility in flexion through a partially confinement with strips of fiberglass and full confinement by fiberglass cloth as illustrated in Fig. 2. Although the simulations on the specimens described in this study are extensive have demonstrated that appropriately designed sheaths in both reinforcement strategies can provide sufficient confinement and buckling retention of bars to achieve high levels of displacement ductility flexing.

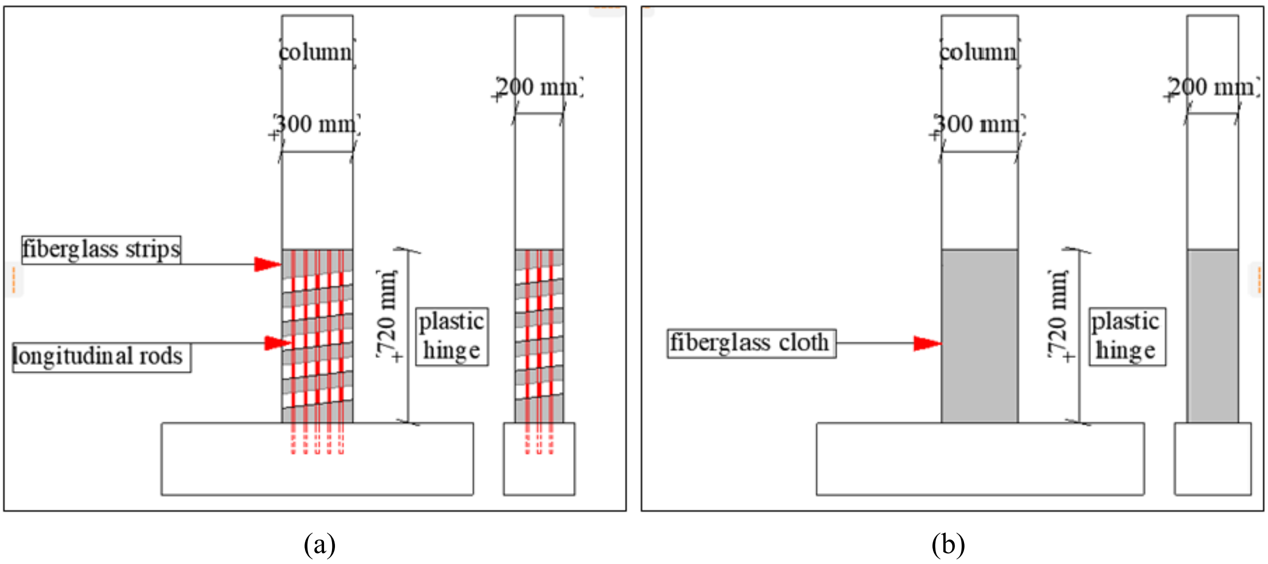


Fig. 2. Improving ductility and shear capacity in columns through seismic retrofit of test specimens: (a) improvement for shear and ductility (partial confinement), (b) improvement for ductility (full confinement).

4. Materials and methods

4.1. Design of test specimens

In this investigation, we modeled thirteen rectangular reinforced concrete columns characterized by a low compressive strength of 15 MPa. The columns had dimensions of 200 mm, 300 mm, and 2000 mm, and were integrated into foundations measuring 300 mm, 300 mm, and 1200 mm. Longitudinal reinforcement was achieved using 12 mm diameter bars, while transverse reinforcement utilized frames with a 6 mm diameter. The columns were subjected to axial compressive force and lateral cyclic loads during analysis, with the first column designated as a reference (C.Ref). The remaining twelve columns were reinforced with varied parameters, organized into three groups. The first group included columns reinforced with longitudinal steel bars of diameters 12 mm, 14 mm, and 16 mm. The second group featured columns reinforced with bars and partially enveloped in a spiral configuration using fiberglass strips with dimensions of 60 x 4 mm. The final group comprised two columns that were both strengthened and enveloped using the aforementioned technology. Moreover, these columns underwent complete wrapping with two and four layers of fiberglass cloth, respectively.

The geometric characteristics and the reinforcement of the columns of the study are illustrated in Fig. 3.

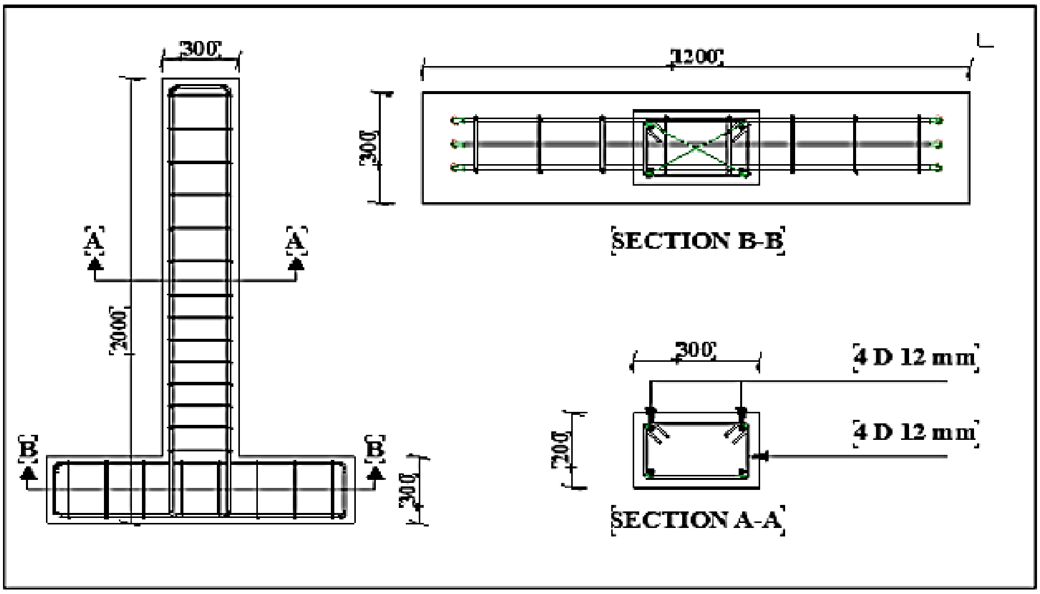


Fig. 3. The detail geometry of specimen along with the cross section.

The specimens were divided in groups, as indicated in Table 1.

Table 1. Classification and Division of Specimens into Groups.

Groups	Column	Bars (mm)	strips	cloth
	C. Ref			
Gr 01	C.JB 12	12	Two layers	/
	C.JB 12 PW	12	Two layers	/
	C.JB 12 P. FW 2L	12	Two layers	Two layers
	C.JB 12 P. FW 4L	12	Two layers	Four layers
Gr 02	C.JB 14	14	Two layers	/
	C.JB 14 PW	14	Two layers	/
	C.JB 14 P. FW 2L	14	Two layers	Two layers
	C.JB 14 P. FW 4L	14	Two layers	Four layers
Gr 03	C.JB 16	16	Two layers	/
	C.JB 16 PW	16	Two layers	/
	C.JB 16 P. FW 2L	16	Two layers	Two layers
	C.JB 16 P. FW 4L	16	Two layers	Four layers

The following specimens names were employed C.JR. Ø P.EW n L, where the symbols in this coding system are:

C : colonne

JB : jacketing by reinforcing bars

Ø : diameter of reinforcement rods 12, 14 et 16 mm

P : partially wrapped by fiberglass strips

F : fully wrapped in fiberglass fabric

W : wrapped

n L : number of layers

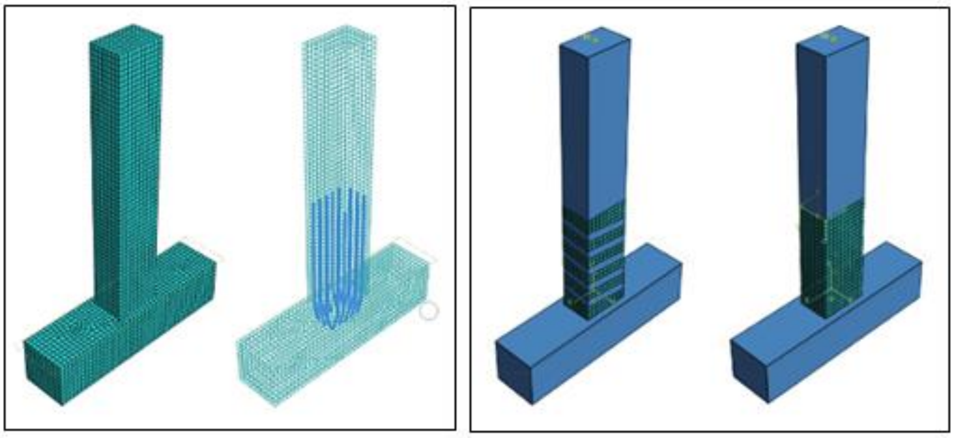
The supported columns were divided into three groups where the first group is

supported by reinforcing rods with a diameter of 12 mm, 14 mm and 16 mm, in

this case the columns are called C. JB Ø in which Ø represents the diameter of the rebars, any 12, 14 or 16 mm, and the details of the reinforcement of this method are shown in Fig. 4. Each of the three groups of this study contains two confinements, the first partial using fiberglass tapes, which is named C. JB Ø PW, and in this way, it means partially wrapped.

Then followed by a second fully confinement using fiberglass strips where it was named C. JB Ø PFW xL and xL in this case, represents the number of wrapping layers, where two cases were adopted in this study, the first with two layers and in which the column is called C. JB Ø PFW 2L and the second with four layers and is called C. JB Ø PFW 4L.

These two confinements are applied in the plastic hinge area at a height of 720 mm from the base as shown in the details of the reinforcement of this method in Fig. 4.



(a) (b) (c) (d)

Fig. 4. Details of the different reinforcements for each series: (a) Reference Column, (b) Columns reinforced only with metal bars -Group 1-, (c) Columns reinforced with glass fibre strips in addition to metal bars -Group 2-, (d) Columns reinforced with fiberglass strips and strips in addition to metal bars -Group 3-.

The reinforcement used in this study took care to preserve the external shape of the columns as well as their surface and dimensions at the hinge. To achieve this, longitudinal reinforcing bars were added to the original concrete, epoxy was used to provide adhesion, and fiberglass strips were used for partial reinforcement. And in the end the fiberglass strips was used to fully reinforce the outer surface.

This technique uses three stages of reinforcement, the first consists of placing rebars inside old concrete, while the longitudinal side of the column is supported by five bars, and the transverse side is supported by three bars as shown in Fig 5. Additionally, the reinforcement bars were anchored to the base of the column as shown in Fig. 6, by digging into the concrete of the base and inserting the bars 13 centimeters with an inclination angle of 15 degrees. The second is the partial confinement, the reinforcement of which is provided by strips of fiberglass, which is considered here as the transverse reinforcement of the column after the previous longitudinal reinforcement with the bars as shown in Fig. 7. The fiberglass strips were chosen for their ease of use and flexibility and because they preserve the dimensions and surface as well as the shape of the original column.

After the two previous reinforcements, a full reinforcement was made with layers of fiberglass cloth at the hinge region, whose column is reinforced with two and four layers as shown in Fig. 8, to study to what extent the thickness of the strips influences the performance and behavior of the reinforced concrete column.

Group 1 - Reinforcement with metal bars only

The samples of Group 1 (C.JB 12, C.JB 14, and C.JB 16), consisting of columns reinforced solely with longitudinal rebars (Ø12, 14, 16 mm).

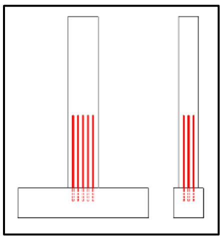


Fig. 5. Columns of Group 1 with reinforcement by Ø 12, 14, 16 mm bars.

The details of anchoring the rebars in the reinforced concrete foundation are shown in Fig 6.

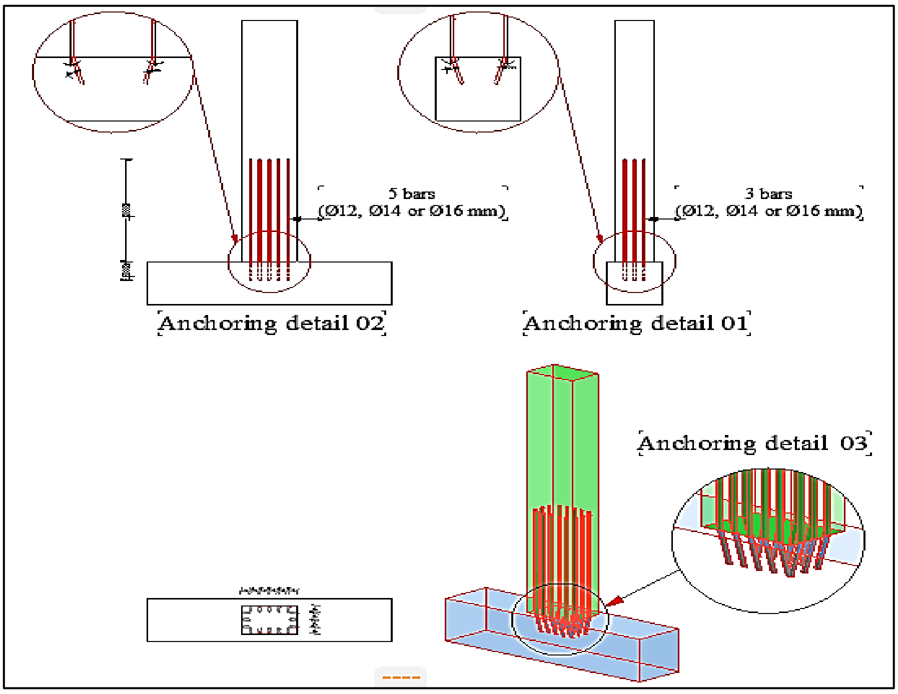


Fig. 6. Details of anchoring the reinforcing bars in the reinforced concrete base.

Group 2 - Reinforcement with fiberglass strips in addition to the bars

The samples of Group 2 included the specimens C. JB 12 PW, C. JB 14 PW, and C. JB 16 PW, reinforced with longitudinal rebars (Ø12, 14, 16 mm), partially wrapped with GFRP strips (60 X 4 mm section).

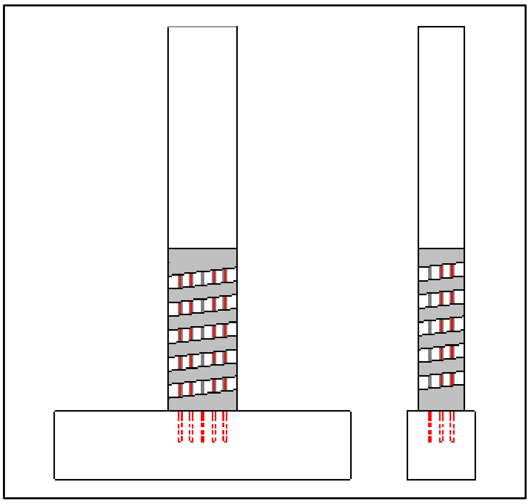
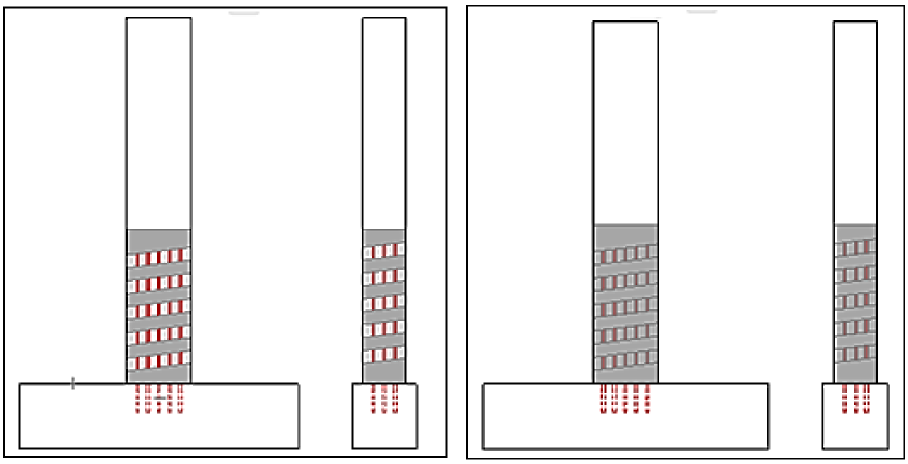


Fig. 7. Columns of Group 2 with reinforcement by fiberglass strips in addition to the bars.

Group 3 - Reinforcement by fiberglass strips and cloth in addition to the bars

The samples of Group 3 included two Subgroup. The first includes the specimens C.JB 12 P.EW 2L, C.JB 14 P.EW 2L, and C.JB 16 P.EW 2L, reinforced with longitudinal rebars (Ø12, 14, 16 mm), more partially wrapped with GFRP strips (60 X 4 mm section) In addition to complete wrapping in two layers of GFRP fabric as shown in Fig. 8, and the second includes the specimens C.JB 12 P.EW 4L, C.JB 14 P.EW 4L, and C.JB 16 P.EW 4L, reinforced with longitudinal rebars (Ø12, 14, 16 mm), more partially wrapped with GFRP strips (60 X 4 mm section) In addition to complete wrapping in four layers of GFRP fabric as shown in Fig. 8.



(a) (b)

Fig. 8. Columns of Group 3 with reinforcement by fiberglass strips and cloth in addition to the bars: (a) complete wrapping in two layers of GFRP fabric, (b) complete wrapping in four layers of GFRP fabric.

4.2. Material properties

This simulation utilizes the physical properties of concrete, rebar, and fiberglass as detailed in Tables 2 to 6.

Table 2. Physical properties of concrete.

Concrete elastic	Plasticity parameters	
Compressive strength 15 MPa	Dilation angle	30.5
E=19364.916 ν = 0.3	Eccentricity	0.1
	FB0/FC0	1.16
	K	0.67
	Viscosity parameter	0.001

Table 3. Physical properties of 12, 14 and 16 mm rebars.

Elastic	Plastic	
	Yield Stress	Crushing strain
E = 184000 ν = 0.3	400.0	0.000
	500.0	0.088

Table 4. Physical properties of 6 mm rebar.

Elastic	Plastic	
	Yield Stress	Crushing strain
E = 218000 ν = 0.3	240.0	0.0000
	300.0	0.1188

Table 5. Elastic properties of orthotropic fiber-reinforced epoxy.

EL (MPa)	ET (MPa)	GLT (MPa)	GTT (MPa)	νTT	νLT
55000	9500	5500	3000	0.45	0.33

Table 6. Damage initiation properties of orthotropic fiber-reinforced epoxy.

σLf,t (MPa)	σLf,c (MPa)	σTf,t (MPa)	σTf,c (MPa)	TLTf
2500	2000	50	150	50

4.3. Description of numerical model

During this study, specimens simulating real- specimens were numerically modeled using Abacus/SA and 2017 software for analysis using the finite element method. The parts modeled in this work are five parts created separately to be then assembled into a single file.

The five parts are modeled as follows

- The concrete column with its base, as they were considered three-dimensional linear brick.
- Reinforcing bars were modeled as 3D lattice elements by solid elements.
- Fiberglass strips which is modeled as 3D shell elements.
- Fiberglass cloths also as three-dimensional shell elements.
- The bars with which the external reinforcement was carried out were designed in the form of 3D lattice elements.

After assembling the basic parts of the specimen of study, which are the concrete column with its base and the longitudinal and transverse reinforcing steel, the strengthening process is initiated according to the previously described techniques.

4.3.1. Modeling the interaction between fiberglass cloth/strip and concrete

The interaction between the fiberglass cloth/strip and the concrete was modeled using ABAQUS constraints to ensure accurate simulation of the composite behavior. The interaction between the concrete and the reinforcing bars was defined using the 'Embedded Region Constraint,' which effectively binds the bars within the concrete, ensuring a consistent stress transfer during loading.

For the interaction between the fiberglass wrapping elements (cloth or strip) and the concrete, a 'Tie constraint' was employed. This method ensures a perfect bond between the wrapping and the concrete surface, simulating an ideal adhesion without slip. The 'Tie constraint' was chosen due to its ability to control the relationship between the master (fiberglass wrapping) and slave (concrete) surfaces, guaranteeing that both materials behave as a single entity under the applied loads.

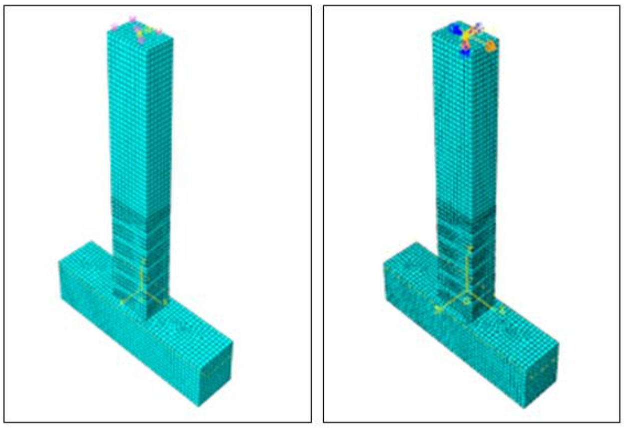
This modeling approach provides a robust framework to study the effects of confinement on the structural performance of the columns, ensuring that the stress transfer between the concrete and the FRP materials is accurately represented.

4.3.2. Loading procedure

The loading procedure, as depicted in Fig. 9, includes two key aspects essential for evaluating the behavior of the specimens under realistic conditions: a monotonous axial load and a periodic lateral load. These loading strategies are crucial for understanding how the FRP-confined reinforced concrete columns respond to both static and dynamic forces.

4.3.2.1. Monotonous axial load

The column was loaded from the top for a vertical compressive force as a monotonous axial load of 270 KN.



(a) (b)

Fig. 9. Loading Procedures for the Specimen: (a) Monotonous Axial Load, (b) Periodic Lateral Load.

4.3.2.2. Periodic lateral load

The cyclic loading procedure was carefully designed to replicate realistic loading conditions that the FRP-confined reinforced concrete columns would experience in practice. As illustrated in Fig. 10, the loading curve for the cyclic loading was developed using a controlled displacement technique.

The lateral displacement was applied in a back-and-forth manner, with a maximum amplitude of 20, simulating the expected service conditions under dynamic loads.

The loading procedure involves incrementally applying and removing loads, allowing for a thorough investigation of the specimen's response to repeated loading cycles. The response of the structure is monitored to capture critical parameters such as stiffness degradation, energy dissipation, and failure mechanisms over the loading cycles.

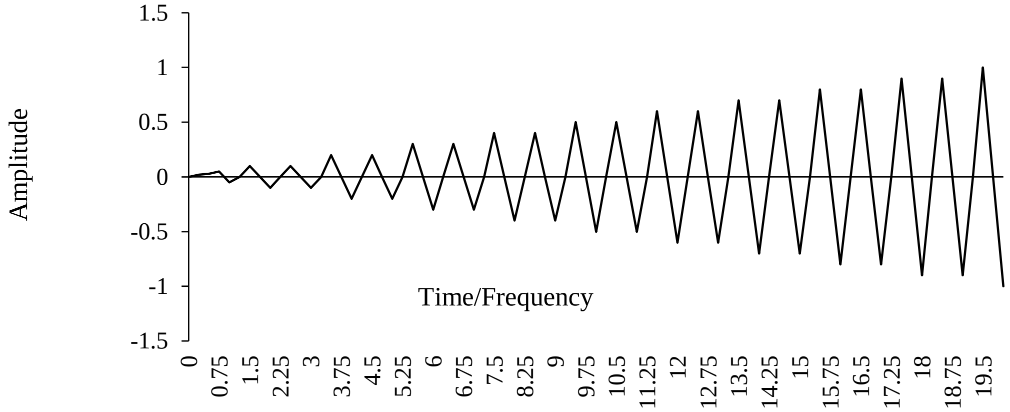


Fig. 10. Cyclic Loading Procedure Curve.

4.3.3. Material behavioral models

In this study, the behavior of concrete was modeled using a concrete damage plasticity model (CDPM) as adopted in the article [20], which incorporates principles from plasticity theory and damage mechanics. The compression damage was calculated using the formula proposed by [33], as illustrated in Fig. 12, while the tensile damage was determined based on the formula from [34], as shown in in Fig. 13.

Fig. 11 illustrates the behavior of concrete under uniaxial loading, with the compressive stress-strain model equations based on the Kent and Park model, incorporating modifications from Hafezolghorani [35] :

$$\sigma_c = \sigma_{cu}\left[2\left(\frac{\varepsilon_c}{\dot{\varepsilon}_c}\right) - \left(\frac{\varepsilon_c}{\dot{\varepsilon}_c}\right)^2\right] \quad \text{(Eq. 1)}$$

$$250000\,\varepsilon_c^2 - 1000\,\varepsilon_c + \sigma_c/\sigma_{cu} = 0 \quad \text{(Eq. 2)}$$

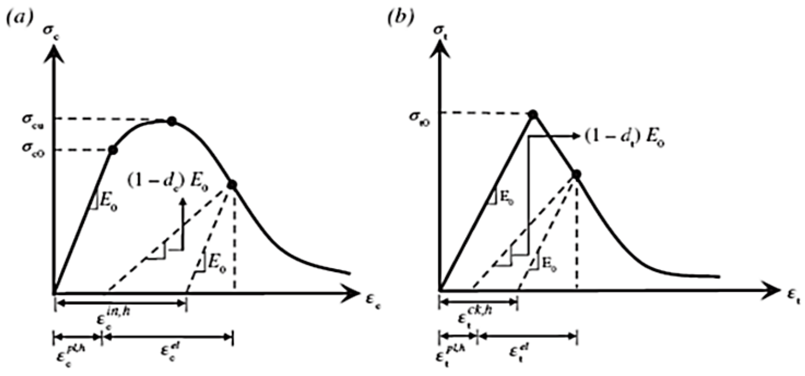
Where σ_{cu} represents the compressive strength of the concrete at 28 days, $\dot{\varepsilon}_c$ is the peak strain corresponding to σ_{cu}, and ε_c is the strain experienced by the concrete.

$$\varepsilon_c^{\,in,h} = \varepsilon_c - \sigma_c/E_0 \quad \text{(Eq. 3)}$$

$$d_c = 1 - \sigma_c/\sigma_{cu} \quad \text{(Eq. 4)}$$

$$E_c = 5000\sqrt{\sigma_{cu}} \quad \text{(Eq. 5)}$$

Where $\varepsilon_c^{\,in,h}$ denotes the inelastic strain, d_c is the damage parameter for compression, and E_c represents the Young's modulus.



(a) (b)

Fig. 11. Concrete's behavior when subjected to uniaxial loading – Hafezolghorani - [35]: (a) Compression, (b) Tension.

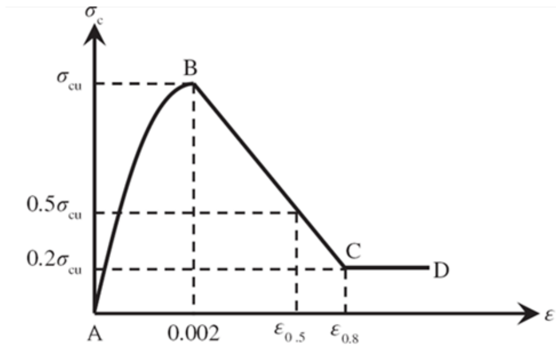


Fig. 12. Model for confined and unconfined concrete -Kent & Park - [33]

Fig. 14 illustrates the tension softening curve, along with the tensile stress-strain model equations derived from Massicotte model [34], incorporating modifications by Allam [36].

$$f_t = 0.7\sqrt{f_{c28}} \quad \text{(Eq. 6)}$$

$$d_t = 1 - \sigma_t / \sigma_{t0} \quad \text{(Eq. 7)}$$

$$\varepsilon_t^{ck,h} = \varepsilon_t - \sigma_t / E_0 \quad \text{(Eq. 8)}$$

Where f_t represents the tensile strength of concrete at 28 days, d_t is the damage parameter, and $\varepsilon_t^{ck,h}$ denotes the cracking strain.

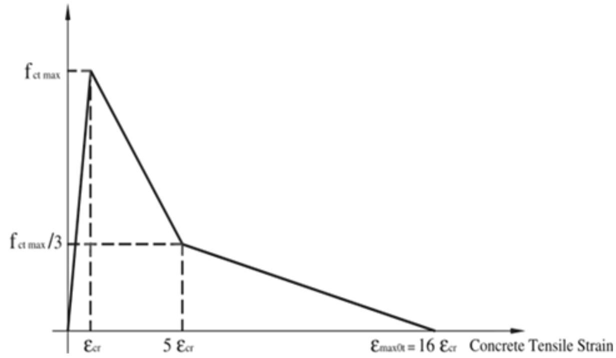


Fig. 13. Tension softening curve suggested by - Massicotte - [34].

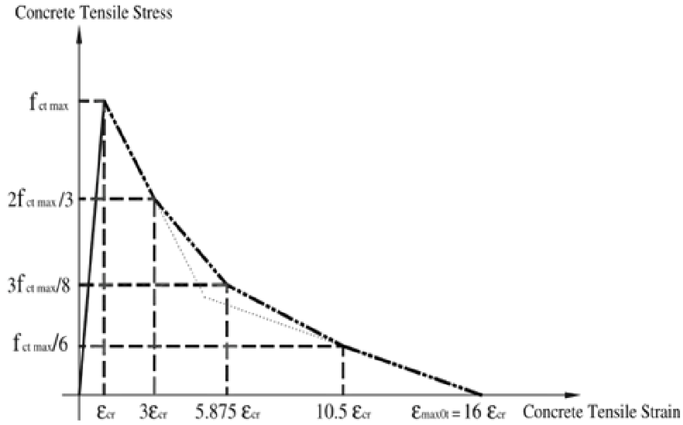


Fig. 14. Tension softening curve modified by – Allam - [36].

The reinforcing steel properties employed by [37] were used in this study. And the behavior of fiberglass was modelled using a type elastic linear by a lamina of 0.5 mm according to ABAQUS/CAE User's Manual [28].

4.3.4. Meshing procedure and mesh sensitivity analysis

In this study, the finite element model was constructed by discretizing five key components to ensure numerical accuracy and stability using Abaqus 2017 as shown in Fig. 15. The model was divided into smaller elements using an approximate global mesh size of 30. This mesh size was selected to provide a balance between computational efficiency and the level of detail needed to capture the behavior of the structural components accurately. The components meshed are as follows:

Concrete Column: The concrete column was meshed using three-dimensional linear brick elements (C3D8R). These elements provide a detailed representation of the stress distribution throughout the column, allowing for accurate simulation of both axial and lateral load effects.

Reinforcement Bars (Longitudinal and Transverse): The longitudinal and transverse reinforcement bars were modeled as 3D lattice elements, ensuring that their interactions with the concrete were accurately simulated. A finer mesh was applied around the reinforcement areas to capture potential stress concentrations.

Steel Support Rods: The external steel rods, used for strengthening, were meshed using 3D lattice elements. A refined mesh was applied around the rods to ensure that their influence on the structural behavior, particularly under cyclic and monotonic loading, was captured accurately.

Fiberglass Strips: The fiberglass strips were meshed as 3D shell elements to simulate their confinement and load-bearing properties effectively. A finer mesh was used at the interface between the strips and the concrete to capture the interaction accurately.

Fiberglass Cloths: Similarly, the fiberglass cloths were meshed using 3D shell elements, with a more refined mesh in areas of high interaction with the concrete and reinforcing bars. This fine mesh helps in accurately simulating the localized stress effects at these interfaces.

A mesh sensitivity analysis was conducted using several mesh sizes to ensure the results were not sensitive to mesh size variations. The global mesh size of 30 was found to provide a good balance between accuracy and computational cost.

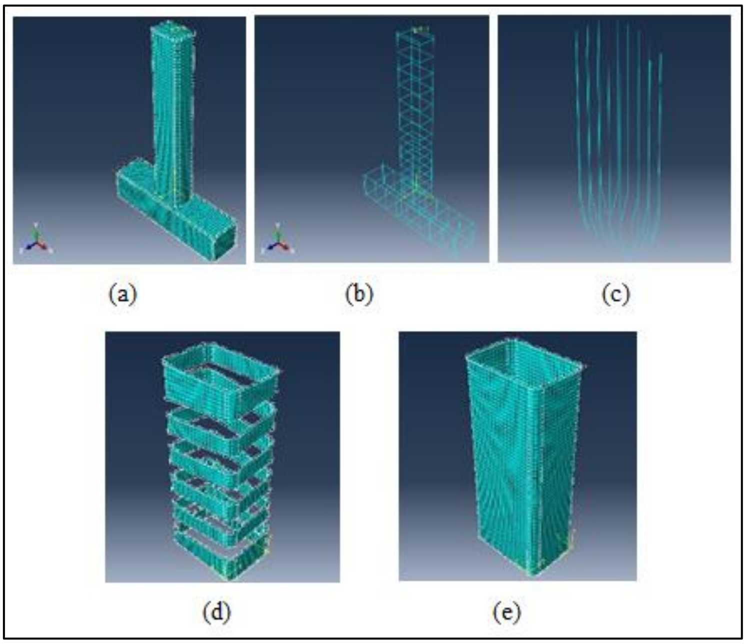


Fig. 15. The mesh shape for each component: (a) Concrete column, (b) Reinforcement bars, (c) Steel support rods, (d) Fiberglass strips, (e) Fiberglass cloths.

4.3.5. Support conditions

In addition to the loading procedures as in the Fig. 16, the boundary conditions were designed to replicate realistic support conditions. The base of the column was constrained from three surfaces : the bottom surface and the two vertical surfaces opposite to the horizontal load. This setup ensures that movement is restricted in all directions (X, Y, and Z) for these surfaces, preventing both translational and rotational displacements. As shown in Fig. 17, this simulates a partially fixed support condition, which aligns with practical applications. The reinforcing bars and concrete were modeled using an embedded region constraint, allowing the bars to behave realistically within the concrete matrix under the applied loads.

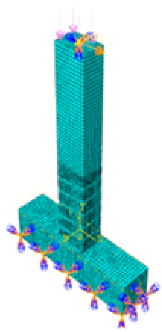


Fig. 16. Support Conditions and Loading Setup for the Concrete Column.

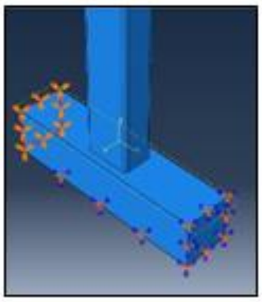


Fig. 17. Boundary Conditions of the Concrete Column: Fully Constrained Base to Prevent.

5. Results and discussion

5.1. Analysis of hysteresis curves

5.1.1. Behavior of the reference column

The results obtained from the reference column are used as a starting point for the analysis. The reference column showed stability in the hysteresis behavior of the columns under load and discharge, thus highlighting the usual behavior of unreinforced columns as shown in Fig. 18.

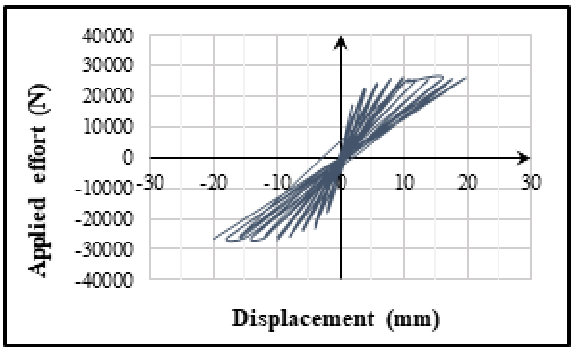


Fig. 18. Reference column effort-displacement curve.

5.1.2. Behavior of the samples of group 1

Group 1 specimens, consisting of columns reinforced only with metal bars (C. JB 12, C. JB 14 and C. JB 16), were subjected to cyclic and monotonic compression tests. Hysteresis curves for these specimens were analyzed and the results obtained are illustrated in Fig. 19.

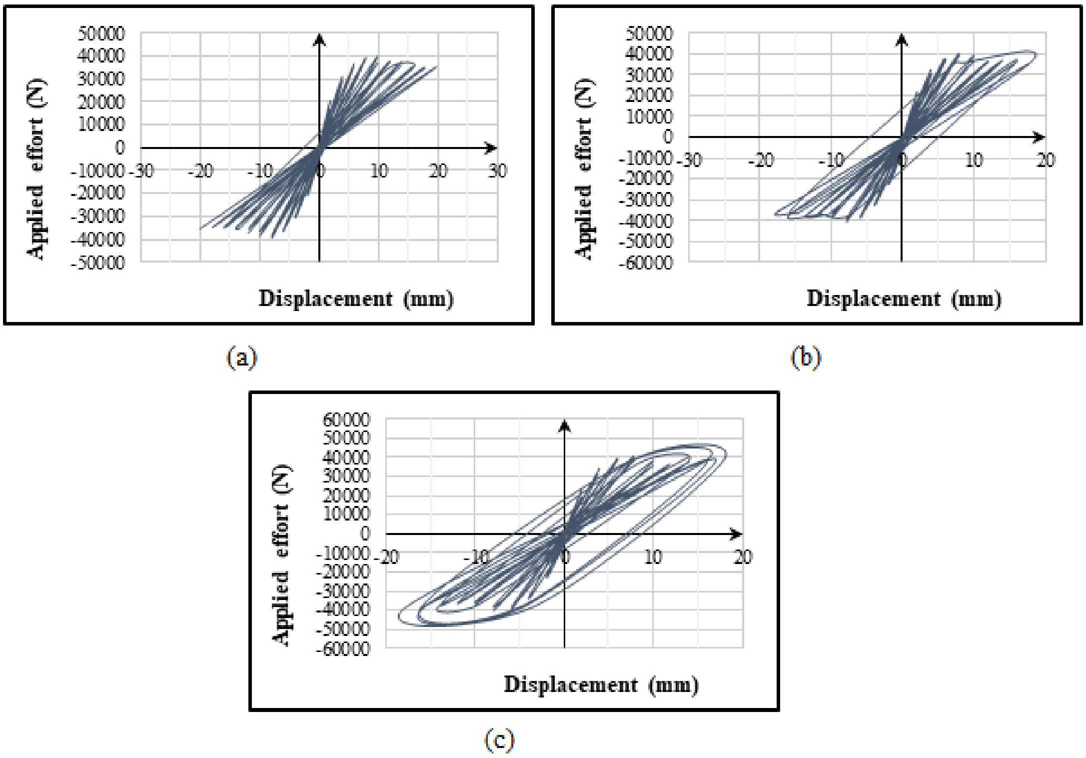


Fig. 19. Force-displacement curve of columns reinforced by metal bars: (a) Column C. JB 12, (b) Column C. JB 14, (c) Column C. JB 16.

The results show that columns C. JB 12, C. JB 14 and C. JB 16, all reinforced with metal bars with diameters of 12, 14 and 16 mm respectively, exhibited stable hysteresis behaviors under load and discharge. However, a relative shift in hysteresis behavior was observed when the diameter of the bars was increased from 12 mm to 14 mm, indicating an influence of bars size on the hysteresis response.

5.1.3. Behavior of the samples of group 2

Group 2 included specimens C. JB 12 PW, C. JB 14 PW and C. JB 16 PW, reinforced with glass fibre strips in addition to metal bars. The hysteresis curves of these specimens were shown in Fig. 20, and analysed in comparison with Group 1.

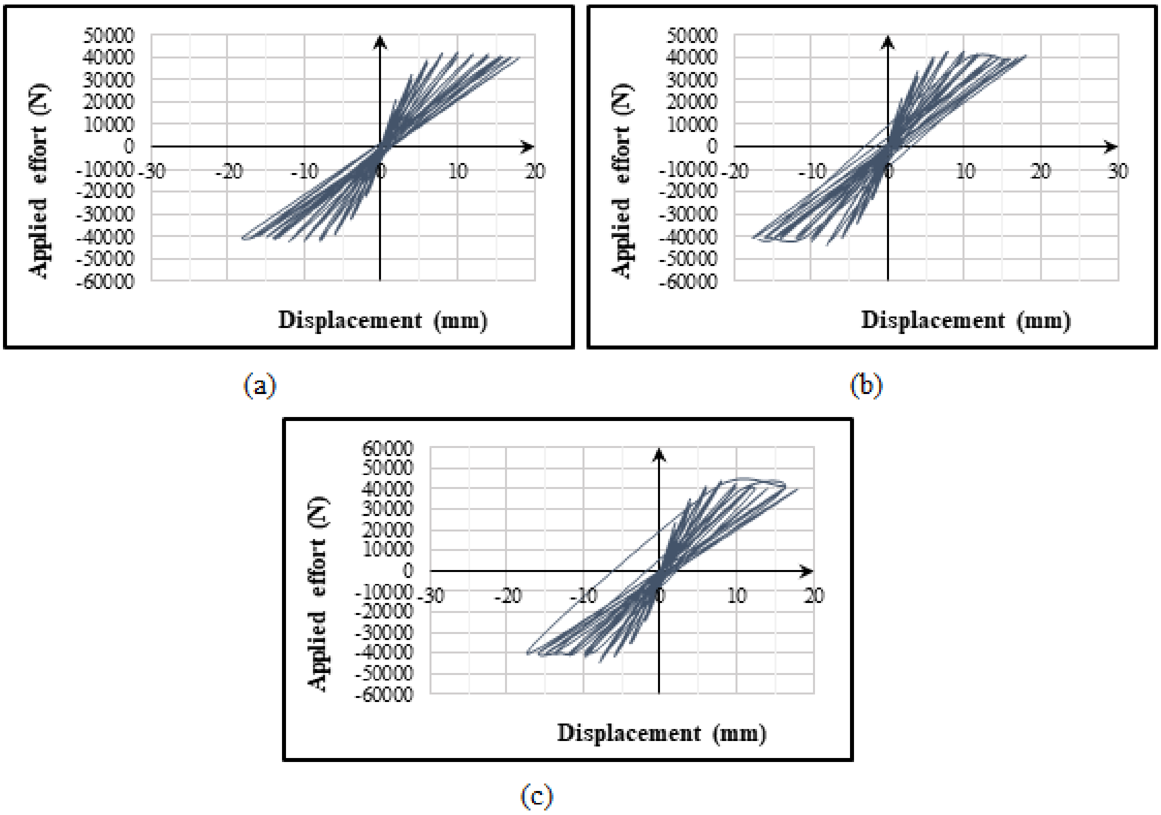


Fig. 20. Force-displacement curve of columns confined with fiberglass strips: (a) Column C. JB 12 PW, (b) Column C. JB 14 PW, (c) Column C. JB 16 PW.

The results indicate that the addition of fiberglass strips helped to improve the stability of hysteresis behavior. Samples from this group showed a significant reduction in deformation and an increase in maximum force compared to Group 1. This suggests that the introduction of glass fibers strips has increased the strength and load-bearing capacity of the columns.

5.1.4. Behavior of the samples of group 3

Group 3 consisted of specimens C. JB 12 P. FW 2L, C. JB 12 P. FW 4L, C. JB 14 P. FW 2L, C. JB 14 P. FW 4L, C. JB 16 P. FW 2L and C. JB 16 P. FW 4L, reinforced with fiberglass strips and strips in addition to metal bars. Hysteresis curves were analyzed to assess the effectiveness of this reinforcement combination. The results were represented in Fig. 21.

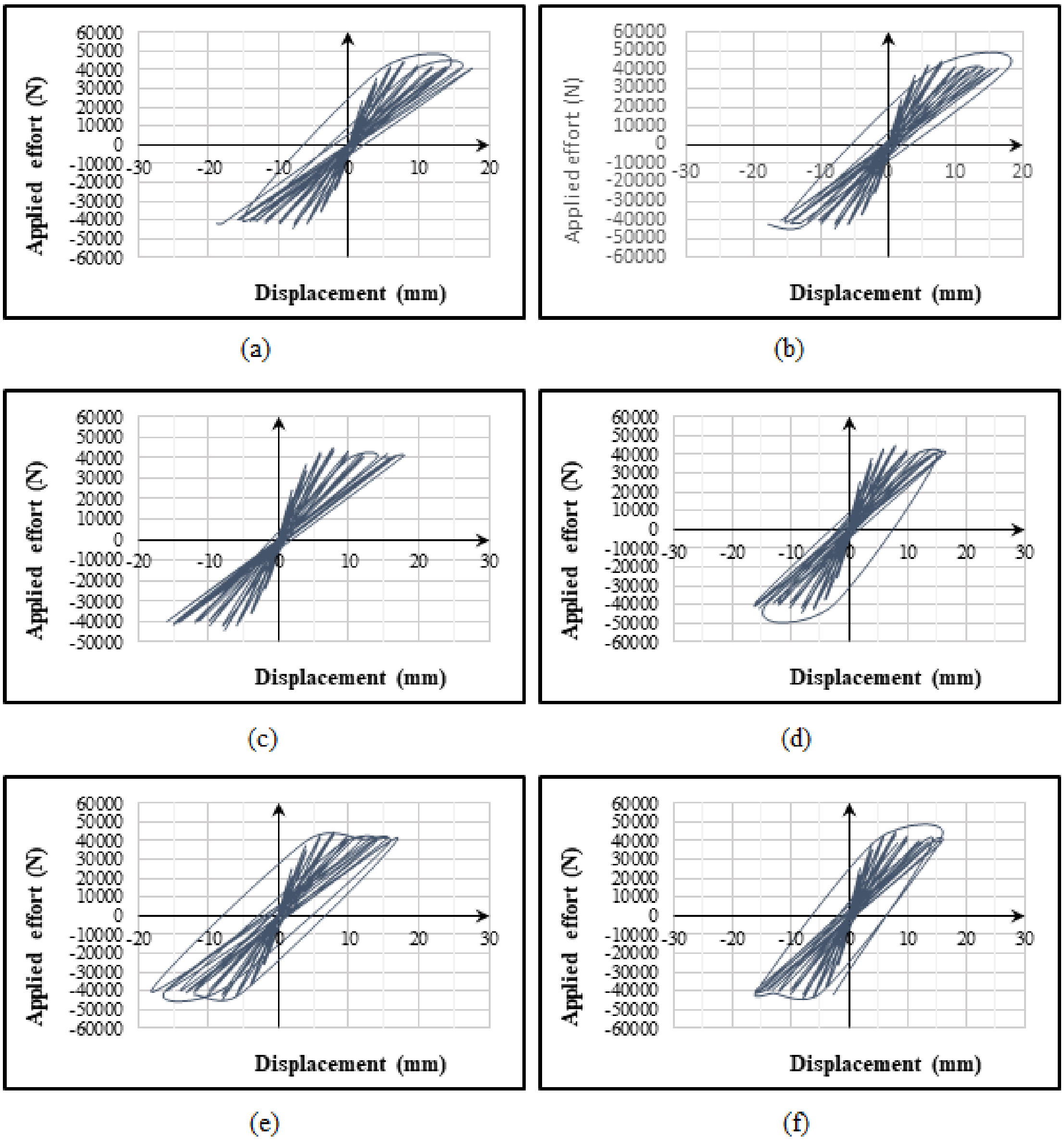


Fig. 21. Force-displacement curve of columns confined with fiberglass cloth and strips in addition to bars: (a) Column C. JB 12 P. FW 2L, (b) Column C. JB 12 P. FW 4L, (c) Column C. JB 14 P. FW 2L, (d) Column C. JB 14 P. FW 4L, (e) Column C. JB 16 P. FW 2L, (f) Column C. JB 16 P. FW 4L.

The analysis of hysteresis curves provides valuable insights into the behavior of FRP-confined reinforced concrete columns strengthened with rods under cyclic and monotonic compression. The hysteresis curves depict the relationship between applied load and deformation, showing the energy dissipation and structural response during loading and unloading cycles. The hysteresis curves for the reference column showed a typical behavior of reinforced concrete under cyclic loading, with a gradual decrease in stiffness and energy dissipation as the number of cycles increased. The addition of metal bars to the column resulted in an improved performance, characterized by higher stiffness and energy dissipation compared to the reference column. On the other hand, the addition of fiberglass strips further enhanced the performance of the column, with increased stiffness and energy dissipation compared to both the reference column and the column reinforced with metal bars only. The hysteresis curves for the column reinforced with fiberglass strips showed the best performance, with significantly higher stiffness and energy dissipation compared to all other configurations.

5.2. Envelope curve analysis

5.2.1. The ref column

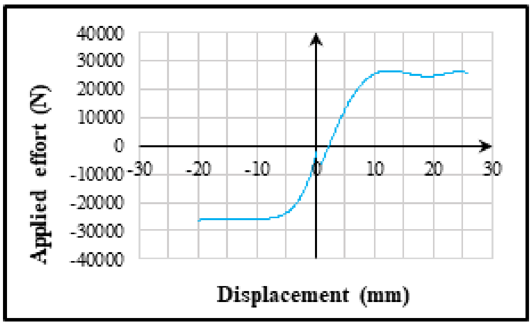


Fig. 22. Envelope curve of reference column

5.2.2. The effect of metal bars on column performance

For columns strengthened only with metal bars, the envelope curve analysis shown in Fig. 23, reveals the typical hysteresis behavior of reinforced concrete columns such that it shows a stable response under load and unloading, indicating limited strength and ductility compared to other groups.

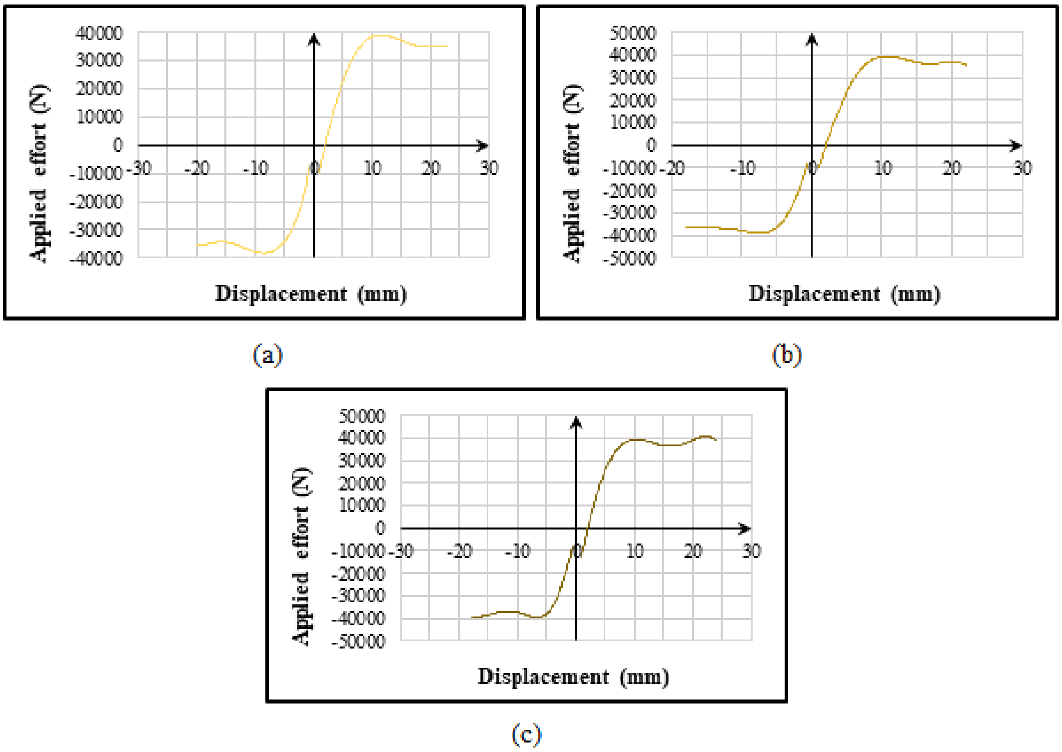


Fig. 23. Envelope curve of columns reinforced by metal bars: (a) column C. JB 12, (b) column C. JB 14, (c) column C. JB 16.

5.2.3. The effect of fiberglass strips on column performance

In the second group with the addition of fiberglass strips to the metal bars, the envelope curve analysis shown in Fig. 24, shows a significant improvement. It shows a noticeable increase in load capacity and a decrease in deformations. This indicates that the addition of fiberglass strips significantly improves the strength and ductility of the column.

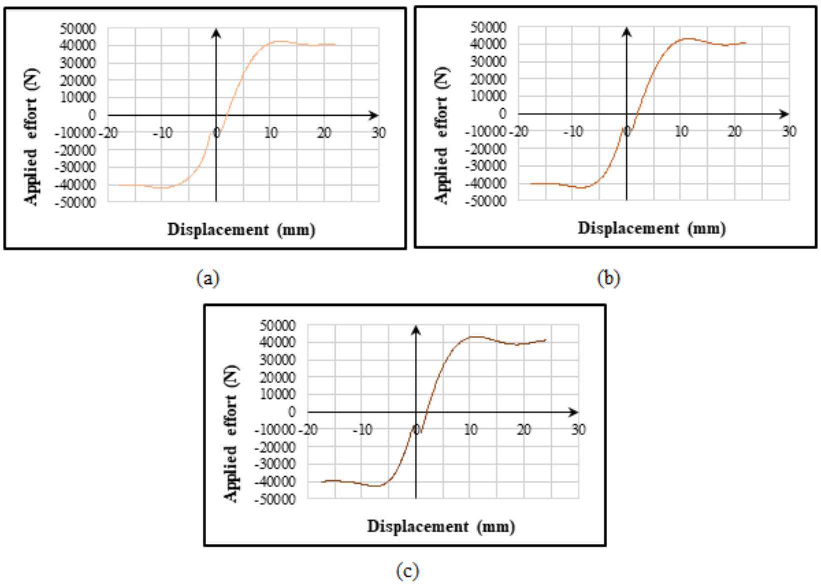


Fig. 24. Envelope curve of columns confined with fiberglass strips: (a) C. JB 12 PW, (b) C. JB 14 PW, (c) C. JB 16 PW.

5.2.4. The effect of fiberglass fabric on column performance

In this group, with the introduction of fiberglass cloth and strips in addition to metal bars, the envelope curve shown in Fig. 25, indicates exceptional performance. So that the curve shows a significant increase in load capacity, resilience, and ductility. The addition of these materials has a synergistic effect further strengthening the column.

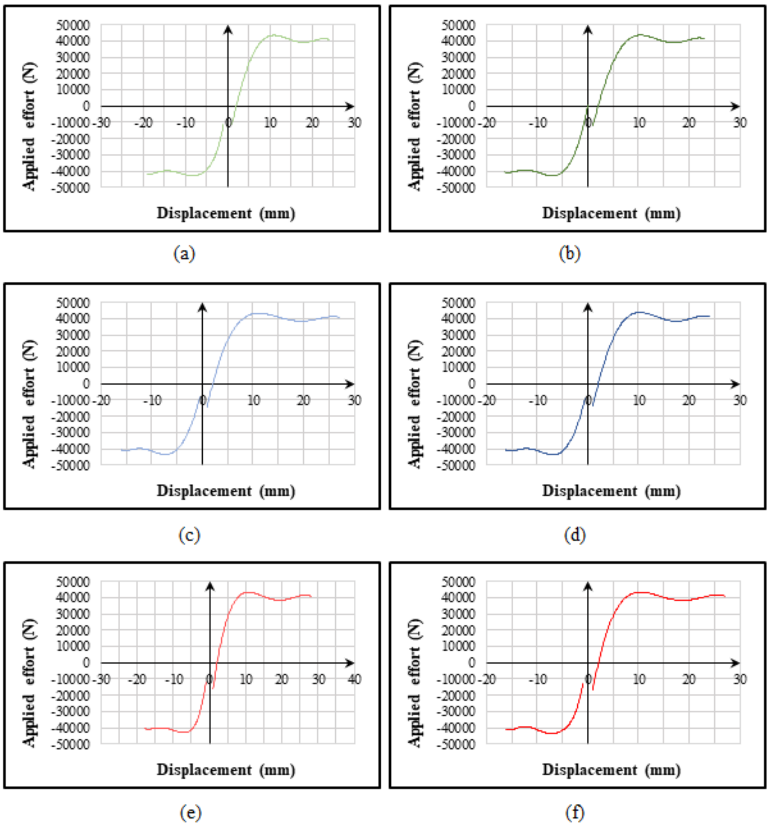


Fig. 25. Envelope curve of columns confined with fiberglass cloth and strips in addition to bars: (a) Column C. JB 12 P. FW 2L, (b) Column C. JB 12 P. FW 4L, (c) Column C. JB 14 P. FW 2L, (d) Column C. JB 14 P. FW 4L, (e) Column C. JB 16 P. FW 2L, (f) Column C. JB 16 P. FW 4L.

Comparing the envelope curves of the three groups as shown in Fig. 26, it can be seen that the group with cloth glass fibers and strips in addition to metal bars has the best performance. The curves show increased strength, high load capacity, and exceptional ductility. On the other hand, the group with only metal bars shows limited performance in terms of strength and ductility.

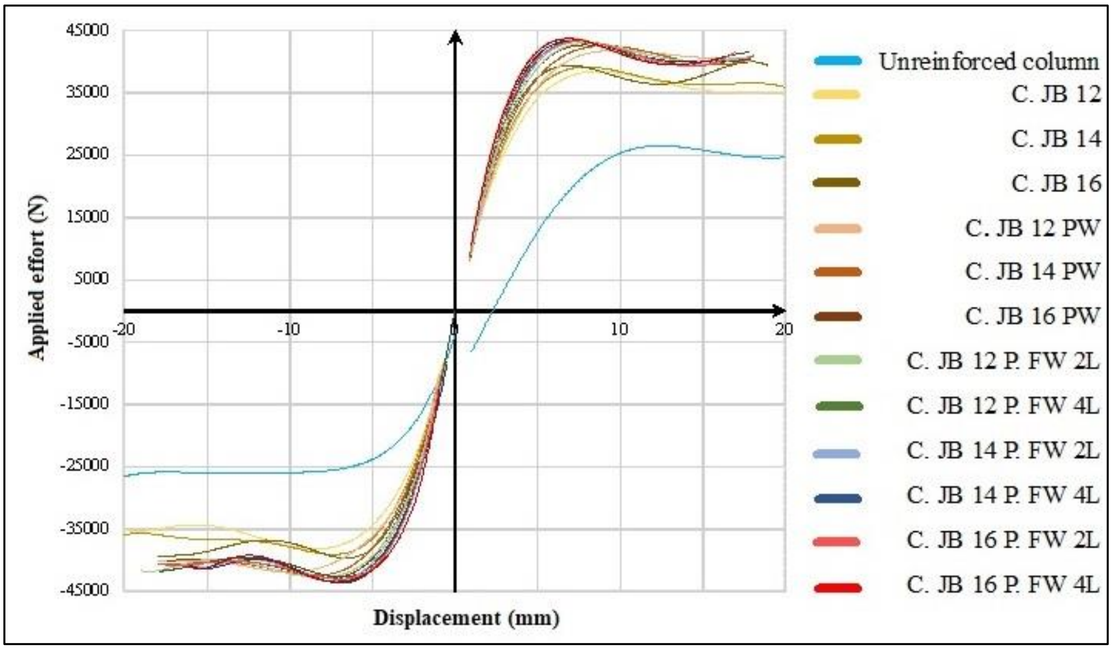


Fig. 26. The Envelope Curve for All Specimens.

The in-depth analysis of the envelope curves confirms the crucial importance of adding fiberglass cloth and strips to improve the performance of reinforced concrete columns. Specimens reinforced with metal bars, glass fiber strips, and glass fiber cloth show a stable hysteresis response, significantly improved load-bearing capacity, and exceptional ductility. These results highlight the effectiveness of this reinforcement technique in resisting cyclic loads.

5.3. Study of modes of rupture

5.3.1. The failure mode of reference column

The failure mode results of the numerical analysis of the reference column are shown in Fig. 27, they detail the stress distribution inside the column. In Fig. 27, a coloring system has been used to represent different stress levels, with red colors indicating areas of high stress and blue colors indicating areas of low stress. This colored distribution provides insight into how forces are distributed within the column and can help identify areas that may be more susceptible to damage or failure. The second Fig. 27, shows the rebar of the column analyzed. This 3D model of the reinforcement allows a more in-depth understanding of the tensions and stresses observed in the first image.

It should be noted that these results depend on many factors, including the type of concrete used, the arrangement of reinforcement, the loads applied and the boundary conditions. These factors can contribute to modifying the stress distribution within the column.

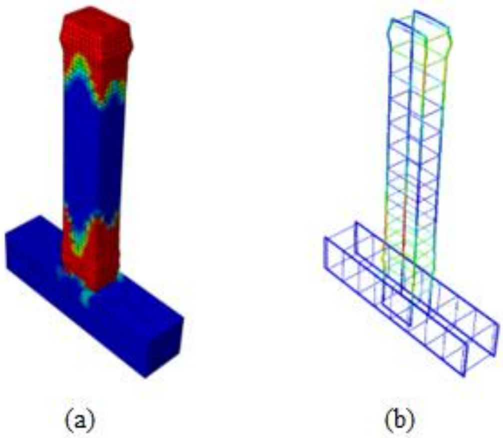


Fig. 27. The failure mode of Reference Column: (a) concrete alone, (b) rebar.

The Fig. 27, shows that the cracking started at the top of the column, near the point of application of the monotonous axial load and then propagated downward along the axis of the column. This situation of rupture can be explained as follows:

- Cracking under unilateral loading: Unilateral loading leads to the formation of small cracks in the concrete. These cracks reduce the strength of the concrete, making it more susceptible to cracking from cyclic loads.

- Cracking under cyclic loading: cyclic loading causes the expansion of cracks resulting from unilateral loading.

Therefore cracks can occur in reinforced concrete columns as a result of the sequential process of unilateral loading followed by cyclic loading. The first one-sided loading process leads to the formation of small cracks in the concrete. The cyclic loading process causes the fracture resulting from the first loading to expand unilaterally.

5.3.2. The failure mode of column reinforced with steel bars only

Fig. 28, shows the loading results for the first group of columns supported by steel bars only.

In terms of strength, columns supported by 16mm diameter steel bars have the highest tensile strength, followed by columns supported by 14mm diameter bars, then columns supported by 14mm diameter bars. 12mm diameter. Compared to the reference column, the columns supported by 16 mm diameter bars have a 20% higher tensile strength. This means that columns supported by 16mm diameter bars can carry a higher load than other columns.

In terms of cracking, columns supported by 16 mm diameter steel bars had the least cracking, followed by columns supported by 14 mm diameter bars, then columns supported by 12 mm diameter bars. Compared to the reference column, columns supported by 16 mm diameter bars have 15% less risk of cracking. This means that columns supported by 16mm diameter bars are less likely to crack under load.

Overall, the study results indicate that columns supported by 16mm diameter steel bars have the highest tensile strength and are less likely to crack than other columns. This is consistent with our previous recommendations that steel rebar provides significant tensile strength, reducing the risk of cracking.

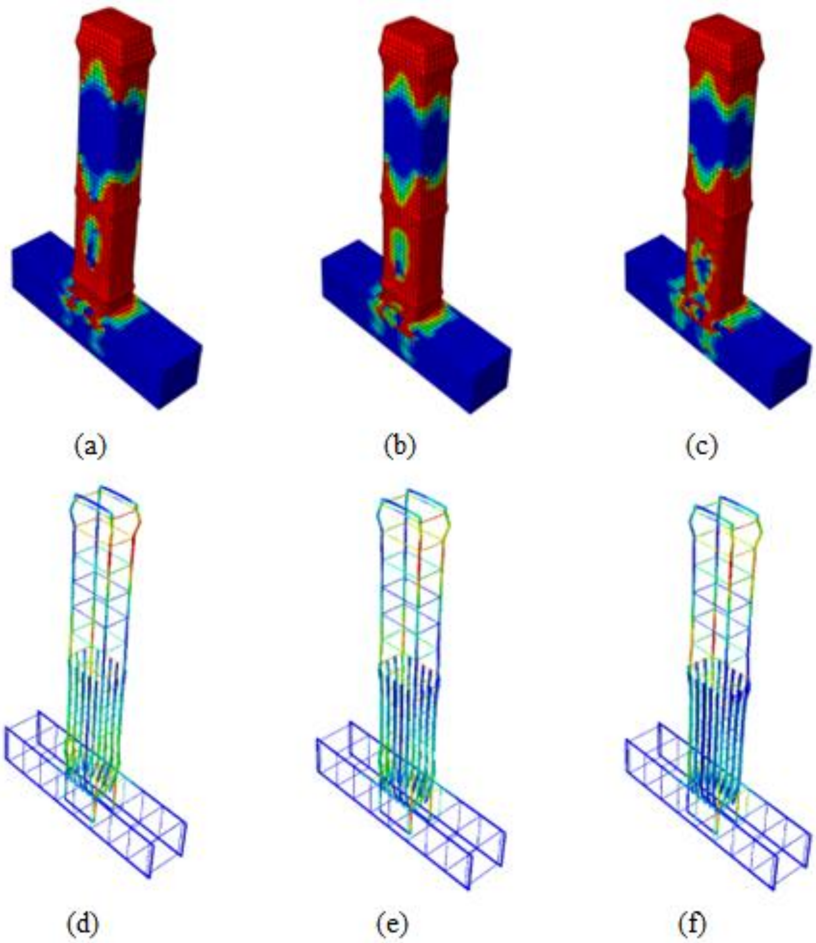


Fig. 28. The failure mode of column reinforced with metal bars only : (a) Column C. JB 12 concrete alone, (b) Column C. JB 14 concrete alone, (c) Column C. JB 16 concrete alone, (d) Column C. JB 12 rebar, (e) Column C. JB 14 rebar, (f) Column C. JB 16 rebar.

5.3.3. The failure mode of column reinforced with fiberglass strips in addition to bars

Fig. 29, shows the loading results for the second group of columns supported by steel bars and fiberglass strips. The three columns were tested with different reinforcement diameters of 12 mm, 14 mm and 16 mm.

In terms of strength, columns supported by 16mm diameter steel bars and fiberglass strips have the highest tensile strength, followed by columns supported by 14mm diameter bars and fiberglass strips, then the columns supported by 12 mm diameter bars and fiberglass strips. This is consistent with our previous assumptions that steel rebar provides significant tensile strength and fiberglass strips provide additional tensile strength. Compared to the reference column, the columns supported by 16 mm diameter steel bars and fiberglass strips have 25% higher tensile strength. This means that columns supported by 16mm diameter steel bars and fiberglass strips can carry higher load than other columns.

In terms of cracking, columns supported by 16 mm diameter steel bars and fiberglass strips are the least cracked, followed by columns supported by 14 mm diameter bars and fiberglass strips, then the columns supported by 12 mm diameter bars and fiberglass strips. This is also consistent with our previous hypotheses that steel reinforcing bars and fiberglass strips reduce the risk of cracking. Compared to the reference column, columns supported by 16mm diameter steel bars and fiberglass cloth strips are 20% less likely to crack. This means that columns supported by 16mm diameter steel bars and fiberglass strips are less likely to crack under load.

In general, the study results indicate that:

Steel rebar helps support the unique vertical load, which reduces stress in the concrete and prevents cracking.

The fiberglass strips act as a crack barrier, preventing crack propagation from the plastic hinge area.

Additionally, fiberglass strips can help improve the strength of the steel itself.

From this point of view, the results demonstrated that the joint use of steel reinforcing bars and fiberglass strips provides additional protection against cracking of columns subjected jointly to cyclic and unilateral loads.

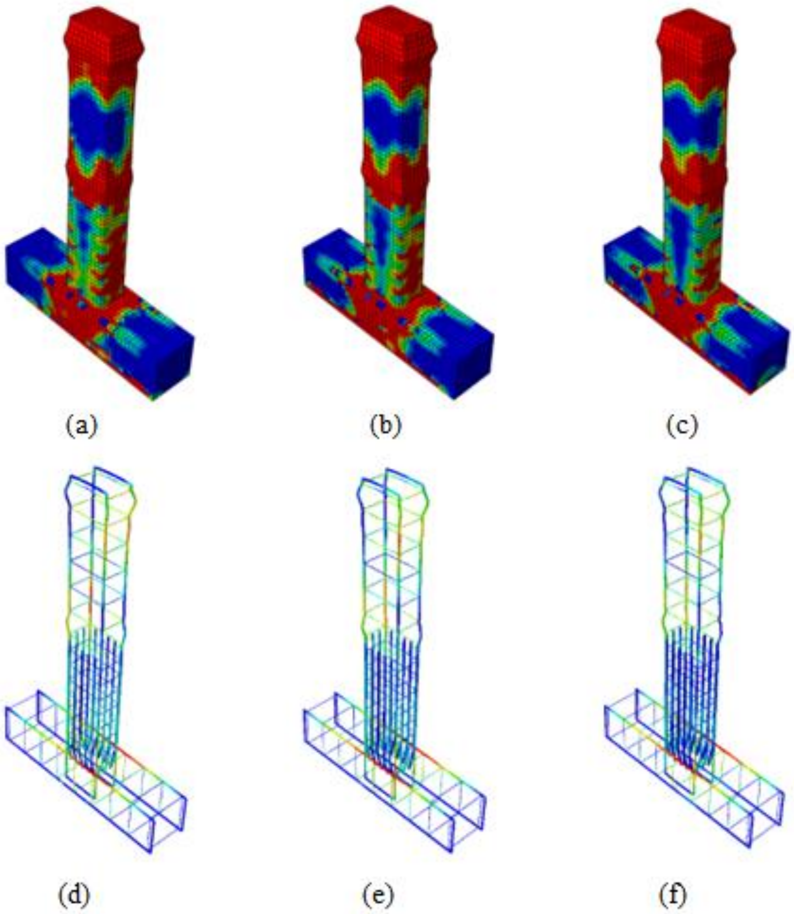


Fig. 29. The failure mode of column reinforced with fiberglass strips in addition to bars : (a) Column C. JB 12 PW concrete alone, (b) Column C. JB 14 PW concrete alone, (c) Column C. JB 16 PW concrete alone, (d) Column C. JB 12 PW rebar, (e) Column C. JB 14 PW rebar, (f) Column C. JB 16 PW rebar.

5.3.4. The failure mode of column reinforced with fiberglass cloth and strips in addition to bars

5.3.4.1. Subgroup 1

Fig. 30, shows the loading results for subgroup three - A - consisting of columns supported by steel bars and fiberglass strips in addition to two layers of fiberglass fabric. The three columns were tested with different reinforcement diameters of 12 mm, 14 mm and 16 mm.

In terms of strength, columns supported by 16mm diameter steel bars and fiberglass strips fully wrapped with two layers of fiberglass cloth have the highest tensile strength, followed by columns supported by 14mm diameter bars and fiberglass strips fully wrapped with two layers of fiberglass fabric, then columns supported by 12mm diameter bars and fiberglass strips fully wrapped with two layers of fiberglass fabric.

This is consistent with our previous hypotheses that full wrapping with fiberglass fabric provides additional strength benefits.

Compared to the reference column, the columns supported by 16 mm diameter steel bars and fiberglass straps fully wrapped with two layers of fiberglass fabric had 30% higher tensile strength. This means that these columns can carry a higher load than other columns.

In terms of cracking, columns supported by 16 mm diameter steel bars and fiberglass strips entirely wrapped with two layers of fiberglass fabric are the least cracked, followed by columns supported by bars of 16 mm diameter. diameter 14 mm and fiberglass strips completely wrapped with two layers of glass fabric, then the columns supported by diameter 12 mm bars and fiberglass strips are completely covered with two layers of fiberglass fabric.

This is also consistent with our previous hypotheses that full wrapping with fiberglass fabric reduces the risk of cracking.

Compared to the reference column, columns supported by 16 mm diameter steel bars and fiberglass straps fully wrapped with two layers of fiberglass fabric are 25% less likely to crack. This means these columns are less likely to crack under load.

Overall, the study results indicate that fiberglass fabric is designed to provide complete protection of columns against cracking.

Additionally, it can be seen that the fiberglass strips and the fabric are interconnected with each other. This indicates that they work as a single unit, providing greater strength and resistance to cracking.

These factors could contribute to the positive results observed in the study.

The results of the third group can be compared to those of the second group. In the second group, fiberglass strips were used intermittently on the columns. In the third group, fiberglass fabric was used entirely around the columns.

We see that the results of the third group are better than those of the second group. For example, columns supported by 16mm diameter steel bars and fiberglass strips and fully wrapped with two layers of fiberglass cloth have 5% higher tensile strength than columns supported by 16 mm diameter steel bars and partially wrapped fiberglass strips.

This difference in results can be explained as follows:

A full fiberglass cloth wrapped around the shaft provides greater protection against cracking.

Wrapping all of the fiberglass fabric around the column allows for a more even distribution of force along the supported area of the column.

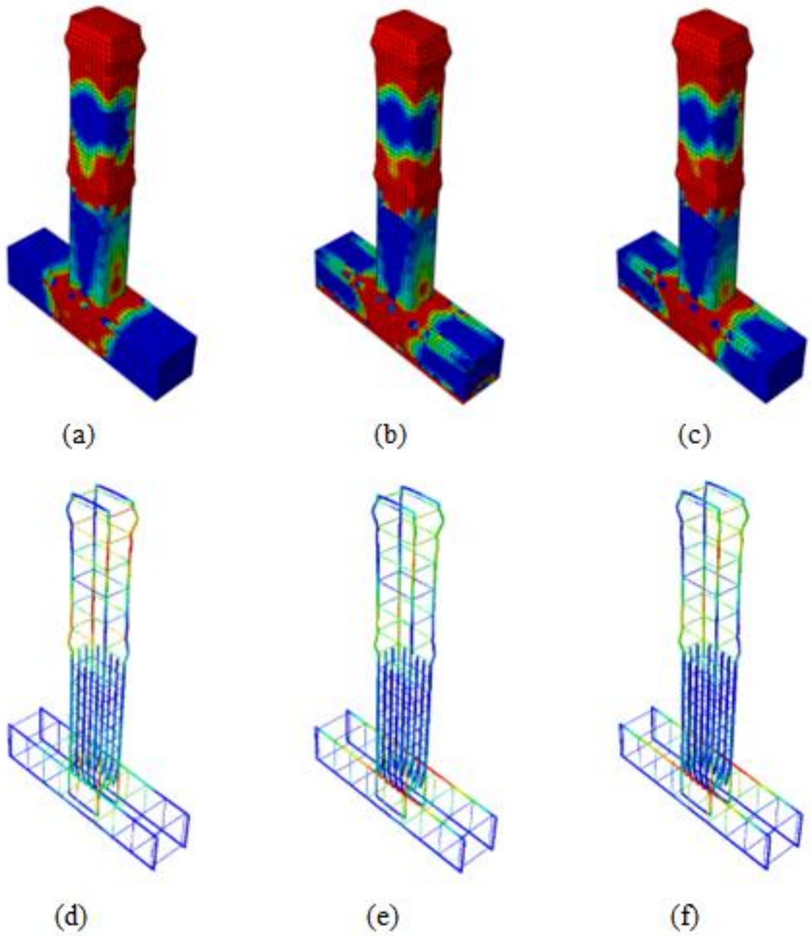


Fig. 30. The failure mode of column reinforced with fiberglass strips in addition to bars : (a) Column C. JB 12 P. FW 2L concrete alone, (b) Column C. JB 14 P. FW 2L concrete alone, (c) Column C. JB 16 P. FW 2L concrete alone, (d) Column C. JB 12 P. FW 2L rebar, (e) Column C. JB 14 P. FW 2L rebar, (f) Column C. JB 16 P. FW 2L rebar.

5.3.4.2. Subgroup 2

Based on Fig. 31, it can be seen that the columns supported by 16mm diameter iron bars and fiberglass strips fully wrapped with four layers of fiberglass cloth have a tensile strength of 50 % higher than that of the reference columns.

Additionally, these columns are found to have a 75% lower probability of cracking than the reference column in the plastic hinge area.

These results are consistent with the results obtained in the previous columns. However, a full wrap with four layers of fiberglass cloth was enough to completely prevent cracking.

One possible reason for the increased strength and crack resistance of the columns is that the complete wrapping of four layers of fiberglass fabric provides sufficient protection against cracking in the plastic hinge area.

Based on the results obtained, the following recommendations can be made:

A full wrap consisting of four layers of fiberglass fabric should be used to provide additional protection against cracking.

Further studies need to be conducted to determine how best to reduce the risk of cracking in columns supported by iron bars and fiberglass cloth strips.

Additional analysis based on the mentioned hypothesis

Based on the hypothesis mentioned, the results can be interpreted as follows:

A complete wrap consisting of four layers of fiberglass fabric provides better protection against cracking than a complete wrap consisting of two or three layers.
The complete four-layer wrap of fiberglass fabric provides a more even distribution of force along the shaft.
The results obtained in the last group can be compared to the results obtained in the previous groups:

In the second group, columns supported by 16 mm diameter iron bars and partially laminated fiberglass strips had 5% higher tensile strength than the reference columns.
In group 03- Subgroup 1, the columns supported by 16 mm diameter iron bars and fiberglass straps were completely wrapped with two layers of fiberglass fabric having tensile strength 30% higher than that of the reference columns.
In the last group, the columns supported by 16 mm diameter iron bars and fiberglass strips were fully wrapped with four layers with 50% higher tensile strength than the reference columns.
These results indicate that complete encapsulation with four layers of fiberglass fabric provides an additional advantage in terms of strength and crack resistance compared to complete encapsulation with two or three layers.

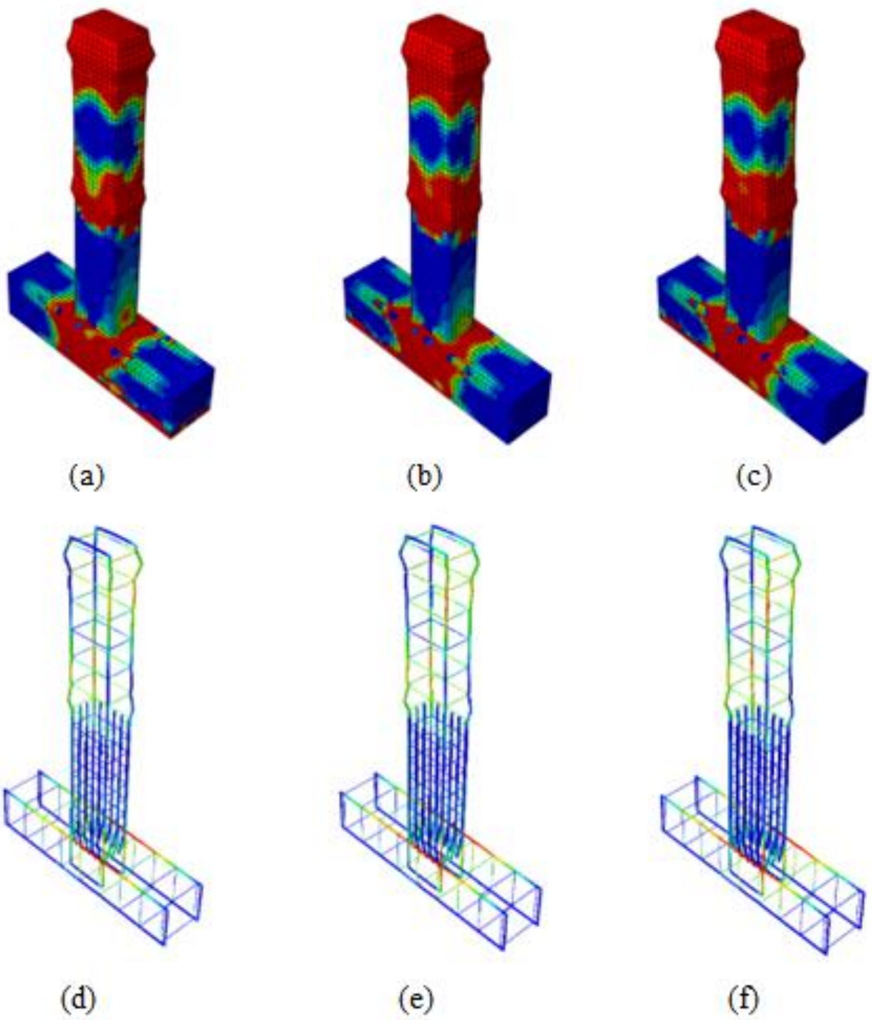


Fig. 31. The failure mode of column reinforced with fiberglass strips in addition to bars: (a) Column C. JB 12 P. FW 4L concrete alone, (b) Column C. JB 14 P. FW 4L concrete alone, (c) Column C. JB 16 P. FW 4L concrete alone, (d) Column C. JB 12 P. FW 4L rebar, (e) Column C. JB 14 P. FW 4L rebar, (f) Column C. JB 16 P. FW 4L rebar.

6. Conclusions

The seismic behavior of low-strength reinforced concrete columns enhanced with steel rods and wrapped with fiberglass strips and fabrics was analyzed using numerical analysis under unidirectional and cyclic loads. The results showed that the reference column experienced brittle shear failure and a lack of ductility, while the column reinforced with steel rods and partially wrapped with fiberglass strips demonstrated better resistance to seismic loads, achieving more stable hysteresis loops with improved energy dissipation and reduced stiffness degradation.

The fully reinforced column showed a significant improvement in seismic performance, with a substantial energy absorption capacity and a marked reduction in stiffness degradation. The third group of columns, fully wrapped with four layers of fiber fabric, exhibited the highest tensile resistance by 50% and a 75% lower likelihood of cracking compared to the reference column, reinforcing the effectiveness of these techniques in enhancing seismic performance.

This study provides a valuable reference framework for researchers and engineers by clarifying the effectiveness of new techniques using composite materials like fiberglass in improving the seismic performance of reinforced concrete columns, which may contribute to enhancing the resistance of structures and reducing economic and seismic risks in earthquake-prone areas. Yet, in order to translate these findings into engineering practices, it is necessary to make the following recommendations:

- Conduct more practical experiments to evaluate the performance of proposed structures under realistic conditions.

- Study the challenges associated with the application of reinforcement techniques using composite materials.

- Conduct a comprehensive thermal study: A thorough study of thermal effects on reinforced columns, whether experimental or numerical, is recommended. Understanding how composite materials react to temperature variations could help better predict the behavior of structures in diverse environmental conditions.

The above recommendations can also guide future research in this field and benefit the practical application of the results of this study.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contribution Statement

Aissa Boumedjane: Conceptualization, Methodology, Software, Writing - Original Draft.

Mouhamed Saadi: Validation, Formal analysis, Data Curation.

Djarir Yahiaoui: Investigation, Resources, Writing - Review & Editing.

Noureddin Lahbari: Supervision, Project administration, Funding acquisition.

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