NUMERICAL INVESTIGATION OF FRP CONFINED RC SQUARE AND CIRCULAR COLUMNS UNDER CONCENTRIC COMPRESSION LOAD

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Abstract

In this study, the behavior of square and circular reinforced concrete (RC) columns confined with fiber reinforced polymer (FRP) composites were compared using the finite element model (FEM) under axial compressive load. The different parameters are considered as the type of FRP confinement such as carbon and glass, grade of concrete, and aspect ratios of the columns. The verified model was used to study the different parameters to investigate the different geometric and materials properties on the axial capacity of the columns. The results revealed a significant increase in the strength and ductility of both the square and circular columns due to FRP confinement. The carbon FRP was slightly more effective in enhancing column strength due to their higher modulus of elasticity compared to the glass FRP. The study also found that higher grades of concrete and lower aspect ratios led to higher strength and ductility in confined columns. Overall, the study suggests that the use of FRP composites for the confinement of RC columns is a viable method for enhancing their strength and ductility. These findings can be valuable for designing and retrofitting RC columns with FRP composites in practical applications.

Keywords: **RC columns; Circular and square columns; Grade of concrete; FRP; Aspect ratio; Concrete confinement**

Introduction

Reinforced concrete (RC) columns are widely used in building construction as they provide essential structural support. However, these columns are prone to brittle failure when subjected to axial compression. To enhance their strength and ductility, the use of fiber-reinforced polymer (FRP) composites being one of the most effective methods. The FRP composites are known for their high strength-to-weight ratio, corrosion resistance, and ease of application, whch make them attractive option for strengthening and retrofitting existing structures. The effectiveness of FRP confinement for enhancing the strength and ductility of RC columns has been extensively studied, and significant improvements have been achieved in their performance.

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Mostofinejad *et al*. (2015) studied the rectangular RC columns confined with CFRP and the influence of corner radius and aspect ratio of cross section. These columns' behavior was affected by corner radius and aspect ratio. They found that load concentration around sharp corners in FRP-wrapped sections reduced the CFRP's ability to improve column behavior. Stress accumulation near the corners of rectangular sections is the primary cause of FRP composite premature rupture. Though, confining rectangular columns with CFRP has improved their maximum strength and maximum strain. When rectangular columns enclosed with CFRP have a fixed aspect ratio, increased corner radius improves strength and ultimate strain. Increasing the corner radius of rectangular columns wrapped with CFRP can result in an improvement of the strength and ultimate strain, provided that the aspect ratio of the columns remains constant. In rectangular cross sections, axial and lateral stresses are much higher nearby corners, resulting in stress accumulation and quick FRP failure. Parvin and Brighton (2014) reported that the corner effect could reduce the stress accumulation effect and improve the confinement for higher load-bearing capacity by converting square to circle and rectangle to elliptical shapes. In comparison to other geometries, FRP wrapping is fairly good for circular and elliptical shape columns.

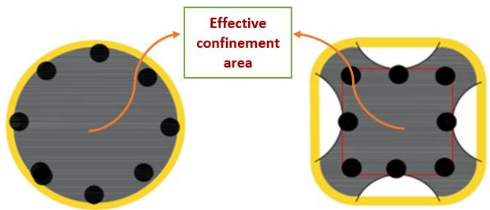

Figure 1. Confinement effect area in different geometries (Parvin and Brighton, 2014)

Cross-section change from circular to a square, the lateral (circumferential) stress over the section perimeter is not uniform for axial compression. From Figure 1, it should be noted that corner radius plays a very important role in confinement (Parvin and Brighton, 2014). Pan *et al*. (2017) investigated the effect of preloading on the strength of RC columns wrapped with FRP composites. They tested 32 circulars and 16 squares columns under various preload conditions and found that increasing preload reduces overall stress and strain. The efficiency of FRP confinement depends on factors such as the type and thickness of FRP, geometry, and concrete grade. Additionally, FRP is more effective in confining circular sections than rectangular or square sections. Li *et al*. (2017) examined the behavior of pre-damaged RC square columns confined with FRP. They found that the level of confinement in square sections is not uniform and varies depending on factors such as confinement pressure, damage level, and corner radius ratio. The effectiveness of confinement is influenced by parameters such as FRP thickness, section geometry, and concrete grade. Circular sections are more effectively confined than square or rectangular sections, and a shorter corner radius can lead to a significant loss of strength. The load-displacement behavior of FRP-wrapped concrete is mainly determined by the corner radius. Li *et al*. (2019) studied 46 concrete columns with various corner radiuses such as 0, 15, 30, and 45. The strength development from FRP jacketing for damaged concrete RC columns is related to the corner radius of prismatic sections, just like it is for undamaged FRP-wrapped RC columns. As the corner radius shrinks, the efficiency of confinement reduces, resulting in a reduction of maximum stress. When there is existing damage in the sample, the corner radius's ability to improve confinement efficiency is less effective than it would be in a sample without damage. The effect of the corner radius becomes more substantial as the pre-damage level rises, with specimens with a smaller corner radius having a greater ultimate strain ratio. The existence of fractures at the corner radius decreases the sharpness of the corner during the reloading process and minimizes stress concentration, which could lead to premature FRP rupture. The rise in confinement strength is also affected by the corner radius. The strength of non-circular elements such as squares and rectangles is increased by increasing the corner radius. A narrow corner radius reduces strength greatly when compared to flat sides due to greater stress accumulation around all corners. The significance of the cross-section aspect ratio on RC columns covered in CFRP sheets was explored. And it was shown that CFRP which is externally bonded improves the strength of members, resists substantial deformation under load, and provides good confinement. Strength increases with the layers of CFRP (EI.Khair, 2021).

Significance of the research

While recent studies have investigated the behavior of FRP-confined RC square and circular columns under different parameters. However, there is a room on the comparison between two column types (circular and square). Most studies have focused on the behavior of either square or circular columns, without directly comparing the two types under similar conditions. Also, there is limited research on the behavior of FRP-confined columns with different aspect ratio and combination of CFRP and GFRP composites. Besides, some studies investigated the effect of aspect ratios on the behavior of confined columns, there is still a lack of understanding of the optimum aspect ratio for both square and circular columns. Addressing these gaps in the literature could provide valuable insights into the behavior of FRP-confined RC columns and inform the design of more efficient and cost-effective retrofitting techniques for existing RC structures. Another gap is the limited research on the behavior of FRP-confined columns with a combination of CFRP. Moreover, (Wu and Wei 2010; Mostofinejad *et al*., 2015; Li *et al*., 2017; Farghal, 2018) few researchers investigated the effect of aspect ratios on the behavior of confined columns, there is still a lack of understanding of the optimum aspect ratio for both square and circular columns. Future studies could explore the effect of different aspect ratios on the behavior of FRP-confined RC square and circular columns, and provide insights into the optimum aspect ratio for each column type.

Addressing these gaps in the literature could provide valuable insights into the behavior of FRP-confined RC columns. This could have significant implications for the construction industry, as retrofitting existing structures with FRP composites can enhance their performance and increase their service life.

Methodology

In this study, a numerical comparison of the behavior of FRP-confined RC square and circular columns were conducted. The focus was on the effects of different parameters considered in the research, such as the type of FRP confinement (carbon fiber reinforced polymer - CFRP and glass fiber reinforced polymer - GFRP), grade of concrete, and aspect ratios. The finite element method was used to model the behavior of the columns under axial compression load, and the results were analysed and compared.

Details of FRP material and their properties

In fiber-reinforced polymer composites, the fibers play a critical role in carrying the load and providing the necessary strength and stiffness (Günaslan *et al*., 2014). In contrast, the matrix is responsible for transferring the load from one fiber to another and to the structural member where FRP is applied. The performance of FRP materials can be evaluated based on various factors such as their shape, length, orientation, and mechanical properties. The authors have provided a visual representation of the composite materials in Figure , where the fibers and resins are combined to act as a single material. FRP matrix materials exhibit anisotropic, heterogeneous, and linear elastic behavior up to their point of failure. To increase their strength, fibers can be oriented in uniaxial, biaxial, or multi-axial directions. These materials offer numerous advantages such as being lightweight, resistant to corrosion and chemical attack, highly durable, easy to install, and requiring minimal maintenance.

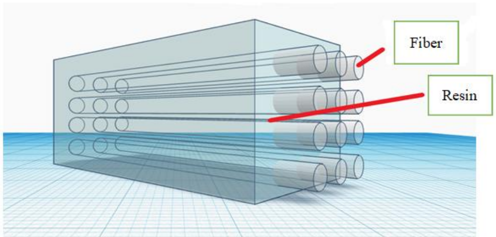

Figure 2. FRP Composite Existing models and material properties utilized in this

In this study, FEM was developed using ABAQUS (ABAQUS, 2014) package for the short FRP confined RC columns under concentric compression load. The concrete is modelled using the concrete damaged plasticity (CDP) model, which is a well-known ABAQUS material model. The CDP model, originally conceptualized in the plastic damage model for concrete by Lubliner *et al*. (1989) which is based on the concrete damage plasticity approach. Material constants are required for the application of this model. It is suitable for modelling concrete under different types of loads and assumes scalar (isotropic) damage. The ABAQUS CDP model is versatile and can be used to represent various semi-brittle materials in different structural elements, such as shells, beams, and solids (ABAQUS, 2014).

The study employs the CDP model proposed by Carreira and Chu (1985). Ahmed Elkady (2021) developed a concrete damage plasticity calculator using MATLAB coding software to create a concrete damage plasticity calculator, as illustrated in Figure 3. The calculator, which was based on Carreira and Chu (1985) model, which was built by Elkady (2021). Before using this calculator, the input value and the type of concrete and the maximum size of aggregate that can be incorporated into a mixture of concrete. Subsequently, the calculator produces an output that encompasses all concrete damage plasticity characteristics, such as compression, tension, dc (Compressive damage variable), and dt (Tensile damage variable) behavior, specific to the concrete grade used.

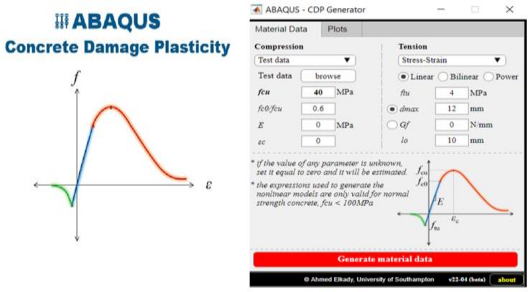

Figure 3. CDP calculator developed by Elkady (2021)

The most frequently used FRP is CFRP with epoxy resin, and the physical and mechanical properties of FRP materials are determined by ASTM D4762-04 (Cepero-Mejías *et al*., 2019).

CFRP with epoxy resin is the most commonly used FRP, and ASTM D4762-04 is used to determine the physical and mechanical properties of FRP materials (Cepero-Mejías *et al*., 2019). Table 1 and Table 2 provide a summary of the FRP material parameters utilized in this study.

Table 1. Mechanical properties of FRP (Santiuste *et al*., 2010; Cepero- Mejías *et al*., 2019)

	E1	E2	G12	G13	G23	μ_{12}
CFRP	126	11	6.6	6.6	4.6	0.28
GFRP	48	12	6	6	4.0	0.28

E1, E2 - Modulus of elasticity of FRP in GPa; G12, G13, and G23 - Shear modulus of FRP in GPa; µ12-Poissions ratio of FRP

Table 2. Strength parameters of FRP (Santiuste *et al*., 2010; Cepero-Mejías *et al*., 2019; Raza *et al*., 2019)

Direction	Strength	CFRP	GFRP
Longitudinal	Tensile strength, XT (MPa)	1950	1200
	Compressive strength, XC (MPa)	1480	800
	Shear strength (MPa)	79	25
Transverse	Tensile strength, YT (MPa)	48	59
	Compressive strength, YC (MPa)	200	128
	Shear strength (MPa)	79	25

Numerical Modeling

Experimental projects are time-consuming, require significant human resources and observation skills, and can be expensive. On the other hand, numerical models can provide accurate results in less time compared to experimental programs. In this study, ABAQUS/CAE package was utilized for modelling short RC columns. The study involved two different grades of concrete, two types of FRP materials, two different geometries, and three different aspect ratios as depicted in Table 3. Table 4 shows the cross-section dimensions of the square and circular RC columns.

Table 3. Short RC column details

Grade of concrete	M20, M30
Type of FRPs	CFRP, GFRP
Geometry	Square with rounded corners & Circular
Aspect ratios	2, 3, and 4

Table 4. Short RC column details

Aspect ratio	Square columns (mm) (b × d × h)*	Circular columns (mm) (d × h)
2	200×200×400	200×400
3	200×200×600	200×600
4	200×200×800	200×800

The designations S2M20CFRP, S2M20GFRP, S2M30CFRP, C4M30GFRP, and others are used to identify the column specimens that are included in this study.The first letter signifies the column's geometry, the second number denotes the aspect ratio of the column,

M20/M30 represents the concrete grade, and CFRP/GFRP indicates column wrapping with CFRP/GFRP, respectively. For example, S3M30CFRP represents an RC square column with an aspect ratio of 3, using Grade M30 concrete, and CFRP wrapping around the corner. The main reinforcement utilized in this study was HYSD Fe 415 grade steel, while the tie bars were Fe250 grade mild steel with yield strengths of 415 MPa and 250 MPa, respectively. Four main rebars with a diameter of 12 mm and six tie bars with a diameter of 6 mm were employed in the columns, and the tie bars were spaced 150 mm apart. The longitudinal reinforcement, and grade of concrete details, are illustrated in Figure 4 and Figure 5. Additional details regarding the reinforcement used are provided in Table 5.

Table 5. Details of reinforcement bars

Elastic Modulus (MPa)	210000
Yield strength of main rebar (MPa)	415
Yield strength of tie rebar (MPa)	250
Area of main rebar (mm^2)	113
Area of tie bar (mm^2)	28.27
Poisson's ratio of steel	0.3

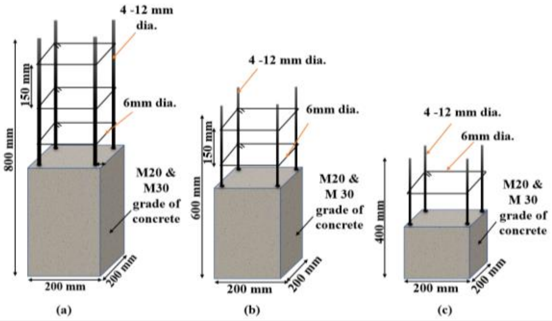

Figure 4. Schematic diagram of c/s and reinforcements of a different aspect ratio of square RC columns

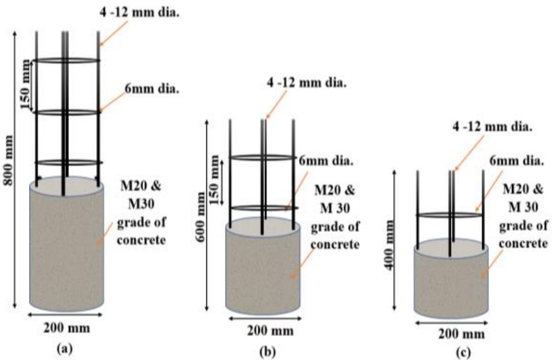

Figure 5. Schematic diagram of c/s and reinforcements a different aspect ratio of circular RC columns

RC Square and circular columns simulation

An RCC column consists of three components: concrete, main rebar, and tie bar. In the ABAQUS package "parts" section, each of these three components is created independently. To illustrate, the S2M20CFRP model is presented here for simulation purposes. The same process can be applied to simulate other square column configurations. The behavior of a concrete column was simulated using ABAQUS/CAE. A three-dimensional (3D) modelling space was selected, and the deformable solid extrusion type was utilized. The material was defined as elastic-isotropic, and the "Concrete Damage Plasticity" material model was chosen in (ABAQUS, 2014) with its associated characteristics specified in Table 6.

Table 6. Details of reinforcement bars

Mass density (N/mm^3)	2.5×10^{-3}
Elastic modulus (MPa)	$5000\sqrt{f_{ck}}$
Poisons ratio of concrete	0.2

The study investigated M20 and M30 concrete grades, which have different elasticity moduli. The column element meshed with a size of 28 (system-generated value) using hexagonal elements with a sweep technique for mesh regulation. The integration modes used were explicit, linear, and C3D8R (Continuum, 3-D, 8 nodes, Reduced integration) for the parameter "3D stress." The ABAQUS-CAE package was used to model the behavior of reinforcing bars and ties. The modelling was done in three-dimensional (3D) space using deformable wire type. The material was characterized as elastic-isotropic, and its behavior was modelled as "plasticity." In this study, ABAQUS FEM generated the initial step by default, and then a user-defined step was created for loading, electrical stimulation, and other requirements. The analysis"of RC short columns was performed using ABAQUS/Explicit with a period of 1 (total time step). To create a realistic RCC column in ABAQUS, the concrete column, main bars, and tie bars must be properly assembled. The assembly process is illustrated in Table 6 and Table 7. For the square and circular column, respectively.

Strengthened RC circular column simulation

The ABAQUS/CAE was used to model the behavior of FRP material for strengthening RCC columns in this investigation. To accomplish this, a 3D model specimen and deformable shell extrusion type were chosen. The mesh size for seeding was selected to be 28, and the explicit element, Linear-reduced integration, and shell family with S4R node were used. A tie constraint was used to attach the FRP sheet to the concrete surface, allowing for load transfer between the two surfaces while also acting as an adhesive material. The FRP wrapping column in ABAQUS is depicted in Figure 8 and Figure 9, where the green colour represents the FRP sheet and the white colour represents the RCC column. A simulation was conducted for columns with square and circular geometries at varied aspect ratios, as shown in Figure 10.

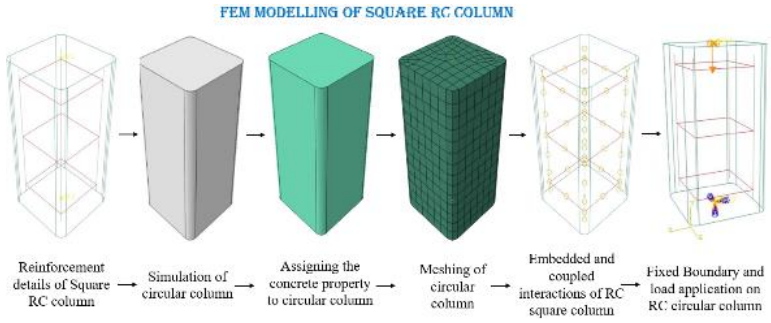

Figure 6. FEM modeling of square columns

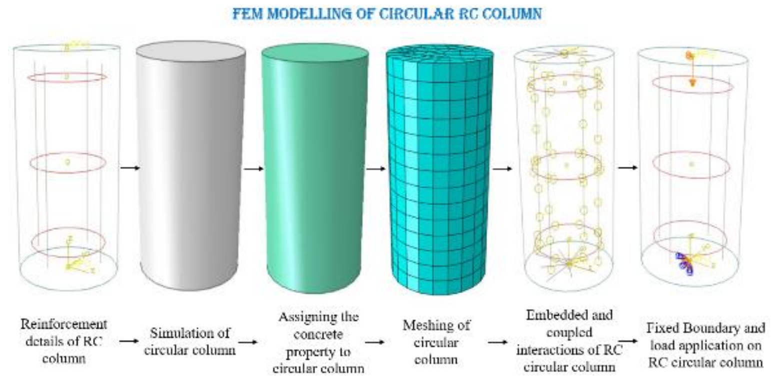

Figure 7. FEM modelling of circular columns

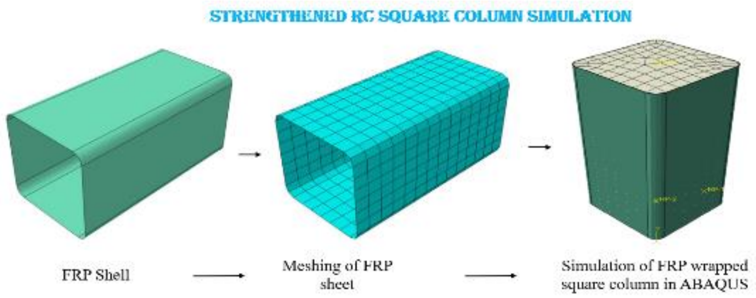

Figure 8. Strengthening of RC square columns

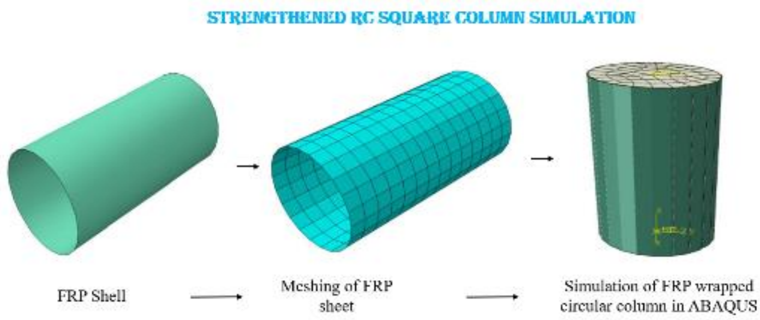

Figure 9. Strengthening of RC circular columns

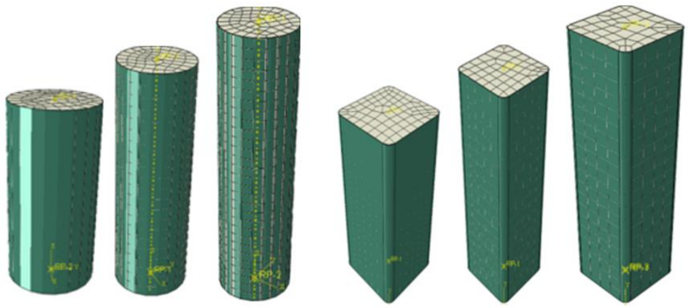

Figure 10. FEM Different aspect ratio of short RC columns simulation in ABAQUS

Results and Discussions

As mentioned previously, the necessary model simulations were performed using ABAQUS. The results were recorded at each step of the process for comparison purposes. The maximum loads for all RC square and circular columns were obtained in stage 1. In stage 2, the preload was applied. In stage 3, FRP material was wrapped around all damaged RC columns, and the maximum load capacity of the column was determined after applying preload and wrapping it with various FRP materials (CFRP & GFRP). The results of each stage are discussed in detail in the following sections.

The notation used to describe the various models in this research is represented as S2 - Square section with Aspect ratio 2; S3 - Square section with Aspect ratio 3; S4 - Square section with an Aspect ratio of 4; C2 - Circular section with Aspect ratio 2; C3 - Circular section with Aspect ratio 3 and C4 - Circular section with an Aspect ratio.

STAGE-2 Results:

To generate damaged columns, it is necessary to apply preload on the RC columns. The preload proposal is shown in Table 8.

Table 8. Proposal preload on RC columns

RC column type	Pre-load proposal on the columns (kN)	
	M20	M30
Square columns		
S2	807.21	1100.40
S3	798.46	1089.03
S4	802.90	1115.80
Circular columns		
C2	665.08	897.73
C3	653.73	880.43
C4	657.69	898.80

STAGE -3 Results:

In the present research paper, the process of repairing the damaged columns involved wrapping them with FRP materials, specifically CFRP and GFRP. The repaired columns were then subjected to further loading until they failed. Table 9 shows the comprehensive summary of stage 3, along with a detailed description of the data collected from ABAQUS.

Table 9. Summary of stage 3 output data

	Max. Stress of Unconfined column (Mpa)	Confined column maximum stress (Mpa)		% of increment strength carrying capacity	
		CFRP	GFRP	CFRP	GFRP
M20					
S2	28.83	32.05	30.27	04.99	11.17
S3	28.51	32.26	30.77	07.92	13.15
S4	28.68	31.82	30.67	06.96	10.97
C2	30.24	35.78	32.30	06.82	18.30
C3	29.73	35.50	32.91	10.71	19.41
C4	29.90	35.64	33.07	10.58	19.17
M30					
S2	39.30	41.00	40.00	1.78	4.32
S3	38.89	41.25	40.25	3.48	6.05
S4	39.85	41.75	41.00	2.88	4.76
C2	40.82	42.97	41.76	2.30	5.26
C3	40.04	43.44	42.17	5.34	8.50
C4	40.87	43.35	42.52	4.04	6.07

Results of axial load carrying capacity of unconfined columns

This section of the paper describes the findings of a study conducted on the axial load-carrying capacity of an unconfined RC column. The results obtained through the numerical investigation are presented about factors such as the aspect ratio, grade of concrete, and geometry.

Geometry

The load-carrying capacity of a column is influenced by its geometry, and this factor has been examined in the present study. The square section and circular column areas used in the experiment were not identical, but the aspect ratios of both geometries were kept equal. Results show that for a given grade of concrete (M20), a square column with an aspect ratio of 2 can carry a load of 1154 kN, while a circular column can only carry 951 kN Therefore, it can be concluded that circular columns have a 21.35% lower load-carrying capacity than square columns. Additionally, for a given grade of concrete (M20), circular columns with aspect ratios of 3 (22.05%) and 4 (22.02%) have a lower load-carrying capacity compared to square columns, as illustrated in Figure 11.

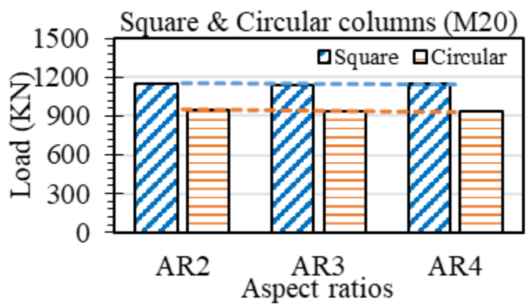

Figure 11. Comparision of load carrying capacity of square and circular columns (M20)

The results of the study Indicate that the load-carrying capacity of a structure is influenced by its geometry, specifically the aspect ratio of the column. The experiment compared the load-carrying capacity of square and circular columns with equal aspect ratios, using M20 grade concrete.

The square columns with an aspect ratio of 2 were found to have a load-carrying capacity of 1154 kN, while the circular columns could only carry 951 kN, indicating that circular columns have a 21.35% lower load-carrying capacity than square columns. The finding is consistent with Li *et al*. (2017) that investigated the load-carrying capacity of different structural shapes. Furthermore, the current study discovered that circular columns with aspect ratios of 3 and 4 had a lower load-carrying capacity than square columns. This is consistent with previous research, which found that circular columns may be less efficient than other shapes for certain aspect ratios and slenderness ratios Li *et al*. (2017). Overall, the current study adds to the existing literature on the load-carrying capacity of various structural shapes and emphasizes the importance of taking a structur's geometry into account when designing for load-bearing capacity.

As per the findings presented in Figure 12, it can be inferred that when the aspect ratio is 2, a square column can carry 22.52% more load compared to a circular column of the same grade of concrete (M30). Similarly, for aspect ratios of 3 and 4, a square column can carry 23.60% and 24.14% more load, respectively, compared to a circular column of the same grade of concrete.

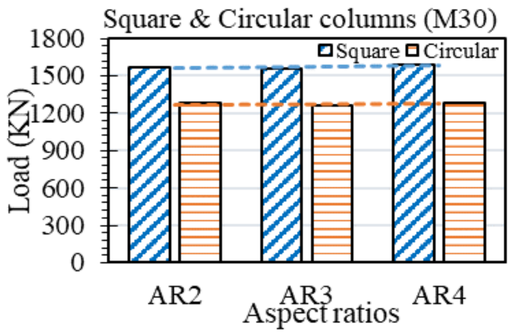

Figure 12. Comparison of square and circular column load-carrying capacities (M30)

Grade of concrete

The load-carrying capacity of RC columns is also influenced by the grade of concrete. Figure 13 and Figure 14 depict the increase in load-carrying capacity of the various RC columns. Results showed that when the grade of concrete is upgraded from M20 to M30, there is a significant increase in the load-carrying capacity of different RC columns. Specifically, for S2, the capacity increases by 36.33%; for S3, it increases by 36.40%; for S4, it increases by 38.97%; for C2, it increases by 34.95%; for C3, it increases by 34.72%; and for C4, it increases by 36.59%.

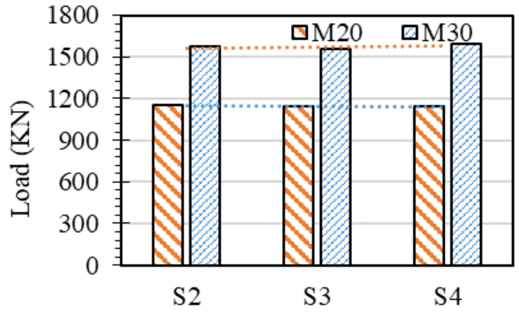

Figure 13. A comparison of the load-carrying capacity of columns of different concrete grades (Square)

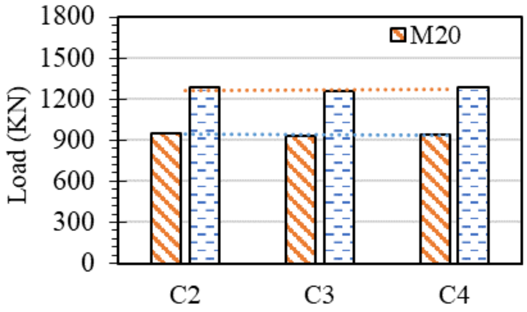

Figure 14. A comparison of the load-carrying capacity of columns of different concrete grades (Circle)

The current study provides the effect of concrete grade on the load-carrying capacity of reinforced concrete (RC) columns. Increasing the concrete grade from M20 to M30 results in a significant increase in the load-carrying capacity of various RC columns. Capacity increases by 36.33%, 36.40%, and 38.97% for square columns (S2, S3, and S4), respectively. Similarly, the capacity of circular columns (C2, C3, and C4) increases by 34.95%, 34.72%, and 36.59%, respectively. The study's findings are consistent with Li *et al*. (2017) that looked at the effect of concrete grade on the load-carrying capacity of RC columns. As a result, the load-carrying capacity of RC columns increased significantly. Furthermore, The current study expands on these findings by examining the effect of concrete grade on the load-carrying capacity of various column shapes (square and circular) and aspect ratios. Overall, the current study adds to the existing literature on RC column load-carrying capacity and emphasizes the importance of considering concrete grade when designing for load-bearing capacity. The stud's findings have implications for the design of RC structures and could be used to help develop building codes and standards.

Aspect ratio

As the aspect ratio of square and circular columns increases from 2 to 3, the load-carrying capacity of the columns decreases for M20 and M30 grades of concrete, respectively. Specifically, for square columns, the reduction is 1.22% for M20 and 1.02% for M30 grades of concrete, while for circular columns, the reduction is 1.82% for M20 and 1.98% for M30 grades of concrete. However, as the aspect ratio further increases from 2 to 3, the load-carrying capacity of the columns improves. For square columns, the capacity increases by 0.6% for M20 and 2.42% for M30 grades of concrete, as depicted in Figure 15 and Figure 16. Similarly, for circular columns, the capacity increases by 0.64% for M20 and 2.06% for M30 grades of concrete, as shown in Figure 17 and Figure 18.

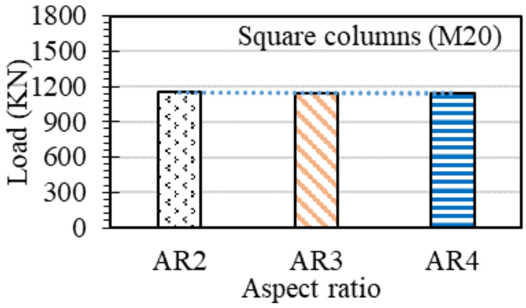

Figure 15. Square column (M20) load carrying capacity comparison with different aspect ratios (M20)

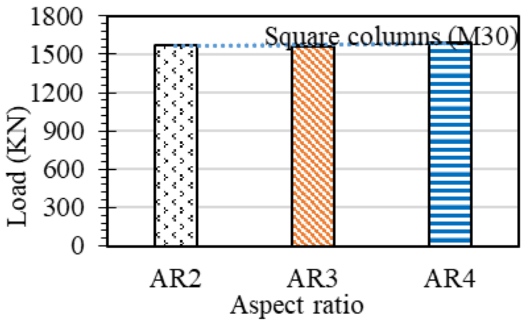

Figure 16. Square column (M30) load-carrying capacity comparison with different aspect ratios

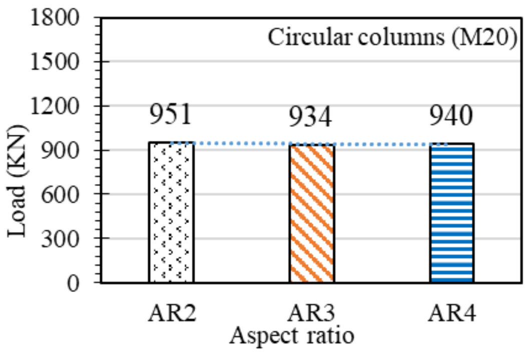

Figure 17. Circular column (M20) load-carrying capacity comparison with different aspect ratios

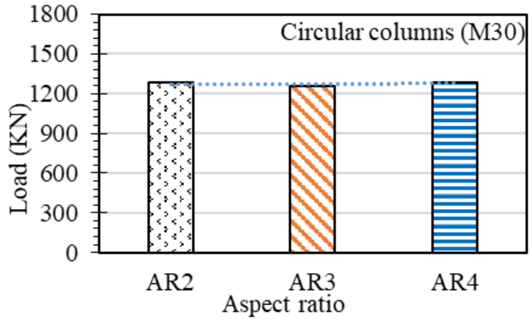

Figure 18. Circular column (M30) load-carrying capacity comparison with different aspect ratios

Results of axial load carrying capacity of confined columns

This section describes the results of axial load-carrying capacity of CFRP and GFRP confined RC columns obtained from the numerical investigation. The analysis is based on various factors, including aspect ratio, grade of concrete, type of FRP, and geometry.

Geometry

Furthermore, the geometry of the column plays a crucial role in enhancing its load-carrying capacity. Generally, circular columns wrapped with any FRP material will exhibit a higher improvement in load capacity than square columns wrapped with FRP material. This is because the corners in square columns result in non-uniform FRP confinement due to the corner effect, which in turn leads to a lower improvement in load-carrying capacity compared to circular columns. Figure 19 illustrates the improvement in load capacity for a given grade of M20 concrete. CFRP-strengthened columns show a greater improvement than GFRP-strengthened columns. When the aspect ratio remains constant, the load-carrying capacity of a circular column will improve more than that of a square column. As displays in Figure 19, C2CFRP exhibits an improvement of 18.3%, while S2CFRP has an observed improvement of 11.17%. Similarly, C2GFRP - 6.82%, S2GFRP - 4.99%, C3CFRP - 19.41%, S3CFRP - 13.15%, C3GFRP - 10.71%, S3GFRP - 7.92%, C4CFRP - 19.17%, S4CFRP - 10.97%, C4GFRP -10.58%, and S4GFRP - 6.96%.

This analysis confirms reinforced concrete column geometry studies. Due to the corner effect, Li *et al*. (2017) and Zhang *et al*. (2021) observed that FRP-wrapped circular columns had a higher load capacity than square columns. The present research also demonstrated that CFRP-strengthened columns had a higher load-carrying capability than GFRP columns. These results underline the relevance of geometry and FRP material in RC column design and strengthening.

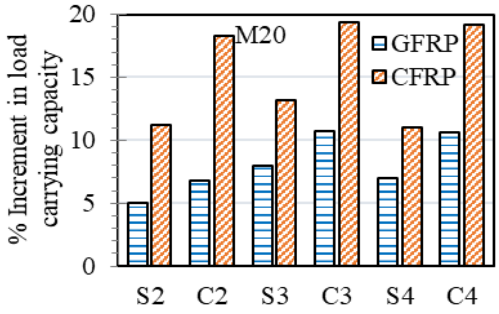

Figure 19. Incremental load capacity due to confinement effect of different columns (M20)

Figure 19 shows the incremental load capacity due to confinement effect of different columns of M20 grade of concete. As displays in Figure 20, for M30 grade concrete, the improvement in load capacity is as follows: C2CFRP - 5.26%, S2CFRP - 4.32%, C2GFRP - 2.3%, S2GFRP - 1.78%, C3CFRP - 8.5%, S3CFRP - 6.05%, C3GFRP - 5.34%, S3GFRP - 3.48%, C4CFRP - 6.07%, S4CFRP - 4.76%, C4GFRP - 4.04%, and S4GFRP - 2.88%. However, it should be noted that the potential for improvement is lower for M30 grade concrete when compared to M20 grade.

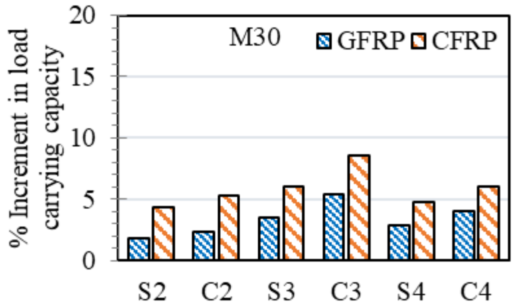

Figure 20. Incremental load capacity due to confinement effect of different columns (M30) Square and circular columns with the different Aspect ratio

Grade of concrete

The impact of aspect ratio on the load-carrying capacity for a specific grade of concrete and type of FRP is negligible. Regardless of the aspect ratio, the load-carrying capacity of columns wrapped with CFRP and GFRP sheets for M20-grade concrete is almost identical. The maximum load-carrying capacities for C2, C3, and C4 columns range from 1115 kN to 1124 kN for M20CFRP and from 1015 kN to 1040 kN for M20 GFRP. For M30CFRP and M30GFRP, the maximum load-carrying capacities for C2, C3, and C4 columns are between 1350 kN to 1365 kN and 1312 kN to 1325 kN, respectively. The stress-strain behavior of circular RC columns for various concrete grades is depicted in Figure 21 and Figure 22.

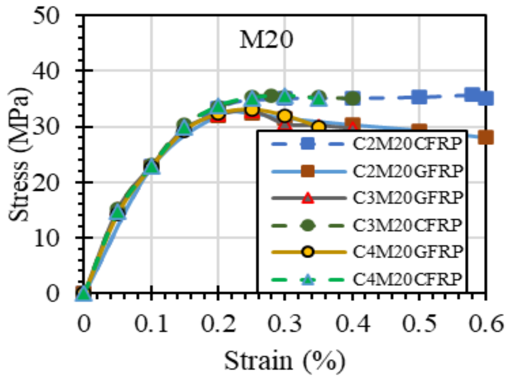

Figure 21. Stress-strain response of confined circular RC columns (M20)

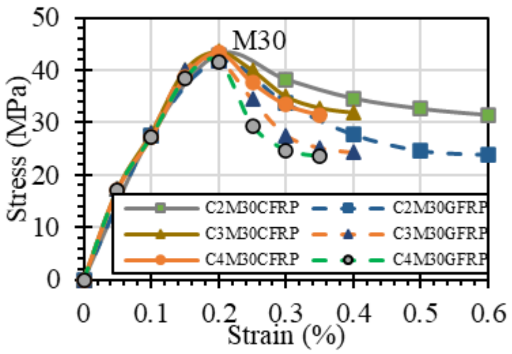

Figure 22. Stress-strain response of confined circular RC columns (M30)

All square RC columns (S2, S3, and S4) have similar or nearly identical load-carrying capacities. Figure 23 and Figure 24 (which depict the stress-strain behavior of square RC columns) reveal that the maximum load-carrying capacities of these columns range from 1271 kN to 1290 kN (10.97%) for M20CFRP, 1210 kN to 1237 kN (6.96%) for M20 GFRP, 1639 kN to 1672 kN (6.07%) for M30CFRP, and 1603 kN to 1637 kN (4.04%) for M30GFRP.

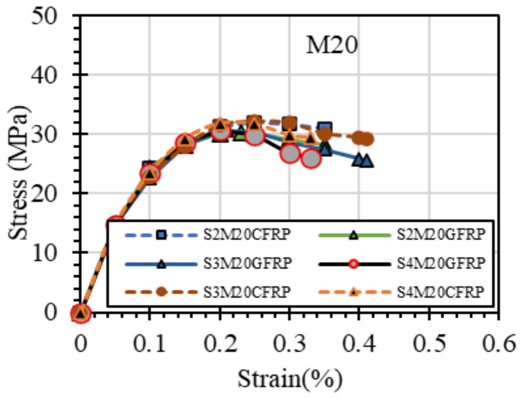

Figure 23. Stress-strain response of confined square RC columns (M20)

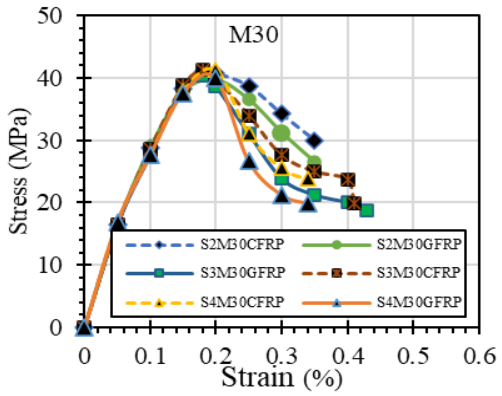

Figure 24. Stress-strain response of confined square RC columns (M30)

Due to the corner effect in square columns, recent research has shown that circular columns wrapped in FRP material enhance load capacity more than square columns. In 2018, Ahmad et al. found that CFRP sheets increased the load-carrying capacity of circular reinforced concrete columns by 60%, whereas square columns increased by 36%. Zhang *et al*. (2021) reported that CFRP sheets on circular columns enhanced load-carrying capacity by up to 42%, while square columns only increased by 32%. These findings emphasize the relevance of column geometry when choosing FRP wrapping material for reinforcement.

From the results presented in Figure 25 and Figure 26, it can be inferred that CFRP-strengthened columns exhibit better performance than GFRP-strengthened columns. Nevertheless, it is worth noting that both types of FRP materials can enhance the load-carrying capacity of M20 and M30-grade concrete.

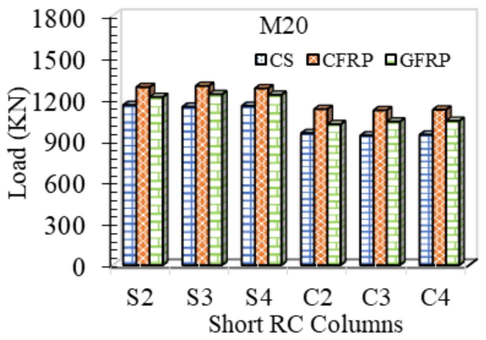

Figure 25. Load carrying capacity of confined and unconfined column specimens (M20)

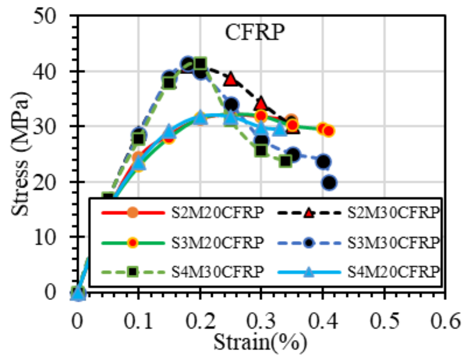

Figure 27. Stress-strain behavior of square columns strengthened with CFRP

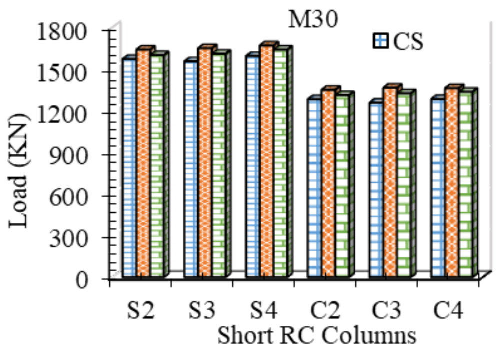

Figure 26. Load carrying capacity of confined and unconfined column specimens (M30)

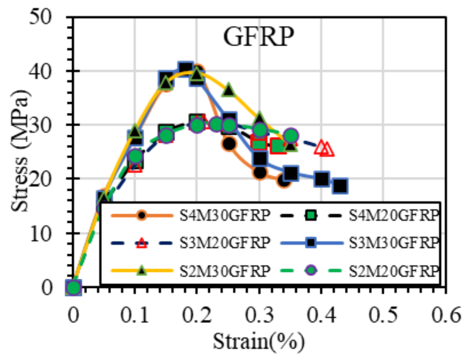

Figure 28. Stress-strain behavior of square columns strengthened with GFRP

Type of FRP

The load-carrying capacity of FRP-wrapped columns is influenced by the type of FRP material used. In this study, both CFRP and GFRP sheets were used for wrapping. The CFRP wrapping demonstrated better performance in terms of axial load carrying capacity of the columns. For M20 Grade, S2, S3, and S4 columns wrapped with CFRP showed an increase in load-bearing capacity with an increase in aspect ratio from 2 to 3, followed by a decrease. In contrast, for M30 Grade, the load increment continued up to S3, as seen in Figure 27. On the other hand, GFRP-strengthened columns exhibited a continuous increase in load-carrying capacity up to S3, followed by a sudden decline from S4 onwards, as shown in Figure 28. Figure 29 depicts the variation in an aspect ratio of circular columns reinforced with CFRP, which shows an increase until it reaches C3, after which it starts to decline. On the other hand, Figure 30 illustrates a circular column reinforced with GFRP, in which the aspect ratio continues to increase continuously until it reaches C4.

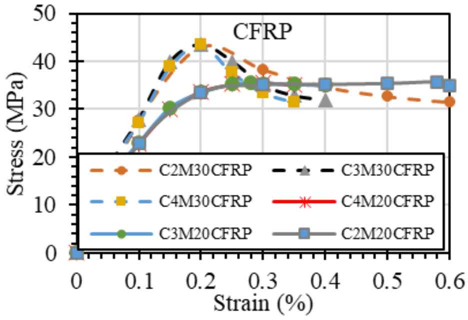

Figure 29. Stress-strain behavior of circular columns strengthened with CFRP

It can be observed that the load-carrying capacity of a column is directly proportional to the grade of concrete, as evidenced by the performance of the CFRP-strengthened column.

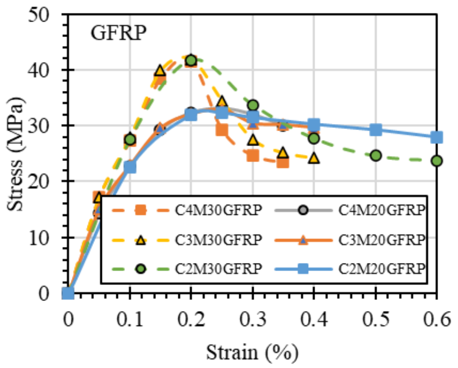

Figure 30. **Stress-strain behavior of circular columns strengthened with GFRP**

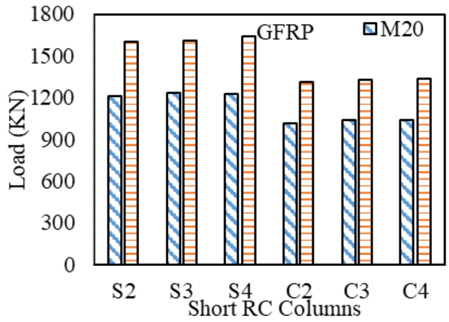

Figure 32. **Load capacity comparison between square and circular columns strengthened with GFRP**

According to the data in Figure 31 and Figure 32, increasing the concrete grade from M20 to M30 enhances the load-carrying capacity of columns confined with both CFRP and GFRP. Figure 31 and Figure 32, indicates that there is no significant impact of aspect ratio on the load-carrying capacity of strengthened columns for both square and circular section.

As shown in Figure 31, the load-carrying capacity of CFRP-strengthened square columns remains close to 1200 KN as the aspect ratio increases, while circular columns with grade of concrete is 20 MPa wrapped CFRP, exhibits a load-carrying capacity of 1100 KN and those wrapped with CFRP with grade of concrete 30 MPa, exhibits a load-carrying capacity of 1400 kN Similarly, for GFRP-strengthened columns shown in Figure 32, the load-carrying capacity of both square and circular columns remains almost constant as the aspect ratio increases from S2 to S4. The maximum load capacity varies close to M20 square - 1200 kN, M30 square - 1600 kN, M20 circular - 1000 kN, and M30 circular - 1300 kN

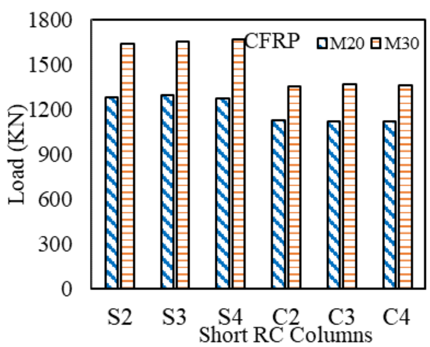

Figure 31. **Load capacity comparison between square and circular columns strengthened with CFRP**

The effects of concrete grade and aspect ratio on FRP-strengthened columns' load-carrying capability are consistent with this text's findings. FRP-strengthened columns' load-bearing capability depends on concrete strength, with higher grades carrying more. Previous study supports aspect ratio findings. FRP-strengthened columns' load-carrying ability is little affected by aspect ratio, especially for circular sections.

Validation of RC columns with expérimental results

Ghali *et al.* (2003) studied the failure of 18 circular RCC columns confined by FRP under small eccentric loads. The influence of eccentricity load on the ultimate load and ductility of confinement columns with differing ratios of slenderness was investigated. The ABAQUS/CAE was utilized to validate these experimental results. Carreria and Chu (1985). CDP model was used in order to create the model for the concrete column. The modelling of concrete and steel followed the same procedure as mentioned and the results are presented in the Figure 33. The maximum load that can be carried by the RC column has an error of 2.02 % according to both the FEM and experimental data.

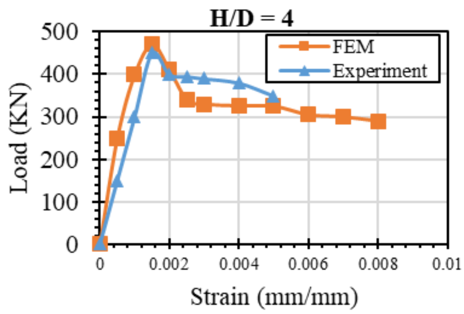

Figure 33. **Stress strain relationship of circular column (Validation model)**

In a similar manner, Benzaid and Mesbah (2013) were also made to a few additional publications for the purpose of validation shown in figure 34 and Figure 35.

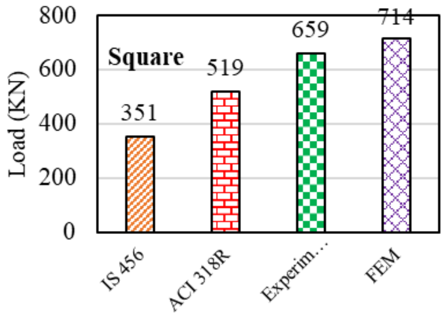

Figure 34. Comparision of maximum loads obtained from different approaches (Short RC square column)

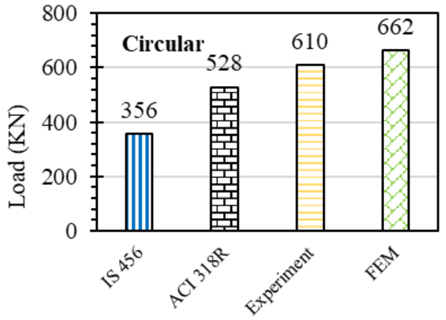

Figure 35. Comparision of maximum loads obtained from different approaches (Short RC circular column)

Conclusions

In this article, we studied the four key factors which could stimulus column behavior: concrete grade, column geometry, aspect ratio, and type of FRP material. It focused on normal-strength M20 and M30 concrete grades, as well as square and circular shape column cross section. Column strengthening was achieved using CFRP and GFRP materials, both of which were 1mm thick. A total of 48 column models were generated and analyzed using ABAQUS. The results of this study are summarized as follows:

- The comparison of the performance of square and circular columns under different conditions provides insights into the behavior of these structures and helps to identify the most effective FRP confinement techniques.
- The research also highlights the importance of the grade of concrete and aspect ratio in the behavior of confined RC columns, which should be considered when designing these structures.
- Increasing the concrete grade from M20 to M30, 38% in the maximum load capacity of both square and circular columns increased. These findings suggest that the load-bearing capacity of concrete is directly correlated with its grade, irrespective of column geometry.
- The numerical results obtained from ABAQUS reveals that the load-carrying capacity of columns is underestimated by IS 456 (2000) and ACI 318R (2019) standards, as these standards are designed with the factor of safety.
- When the aspect ratio of a square column increases from AR2 to AR4, the load-carrying capacity increases by 1280 kN (M20), and 1650 kN (M30) 10.97% for (CFRP-M20) and 6.96% for (GFRP -M20) 4.76%, for (CFRP-M30) and 2.88% for (GFRP-M30). Similarly, for a circular column, the load-carrying capacity reaches approximately 1120 kN (M20), and 1340 kN (M30). 19.17% for (CFRP-M20) and 10.58% for (GFRP-M20) 6.07% for (CFRP-M30) and 4.04% for (GFRP-M30).
- The aspect ratio has minimal impact on the load capacity of both confined and unconfined square and circular columns, which remains consistent across various aspect ratios.
- Confined circular columns exhibit a higher percentage of load-carrying capacity compared to confined square columns. Furthermore, CFRP wrapping columns have superior axial load-carrying capacity performance when compared to GFRP confinement columns.
- The square column carries a more significant load than the circular column. For M20 grade of concrete C2CFRP has an improvement of 18.3%, whereas S2CFRP has an 11.17% improvement observed. Similarly, C2GFRP - 6.82%, S2GFRP - 4.99%, C3CFRP - 19.41%, S3CFRP - 13.15%, C3GFRP - 10.71%, S3GFRP - 7.92%, C4CFRP - 19.17%, S4CFRP - 10.97%, C4GFRP - 10.58%, and S4GFRP - 6.96%.
- For M30 grade of concrete, C2CFRP - 5.26%, S2CFRP - 4.32%, C2GFRP - 2.3%, S2GFRP - 1.78%, C3CFRP - 8.5%, S3CFRP - 6.05%, C3GFRP - 5.34%, S3GFRP -

3.48%, C4CFRP - 6.07%, S4CFRP - 4.76%, C4GFRP - 4.04%, and S4GFRP - 2.88%.

- When the grade of concrete is upgraded from M20 to M30, a GFRP-strengthened square column has a higher increase in strength than a CFRP-strengthened square column, for a given aspect ratio. Conversely, circular columns reinforced with CFRP show greater improvement in strength compared to those reinforced with GFRP.

Based on our observations of the results, we conclude that additional study effort is necessary for the future. The possible work carried out in future mentioned below.

- Normal concrete was used in this project. Instead of the normal grade of concrete, the high strength grade of concrete can be used further to assess the behaviour of columns for high strength grade of concrete.
- This project can be expanded to include different aspect ratios, such as more than 4 or full-scale columns.
- CFRP, GFRP, and epoxy adhesive were used in the completion of this project. Instead of using epoxy glue, different adhesive materials (poly ester and vinyl ester) with different proportions of mixes will need to be studied to determine the optimal mixing proportions of adhesion and FRP material for improved results.
- In the current investigation, a numerical investigation was taken into consideration. In the future, it will be validated through the use of both analytical and experimental work.

Several factors limit the use of FRP construction and repair projects. Difficulties include the need for specific skills for installation, material compatibility problems, and stringent surface preparation specifications. Other concerns include long-term performance, accuracy of structural assessment, and behavior at high temperature. Furthermore, prohibitive expenses and bureaucratic obstacles impede the broader implementation. Maximizing the efficacy and sustainability of FRP wrap applications in the built environment requires addressing these constraints.

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