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Numerical Investigation of the Effect of Hybrid Fibers on the Behaviour of FRP-Reinforced Concrete Columns

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Abstract—

The growing demand for durable and corrosion-resistant concrete structures has led to significant interest in Fiber-Reinforced Polymer (FRP) bars as a viable alternative to conventional steel reinforcement. However, the linear-elastic nature of FRP bars combined with the inherent brittleness of plain concrete frequently results in brittle, catastrophic failures under axial compression. To mitigate these limitations, this study presents a comprehensive three-dimensional (3D) numerical investigation of the performance of square FRP-reinforced concrete columns incorporating hybrid steel fibers (SF) and polypropylene fibers (PPF) under pure axial compression.

Finite Element Models (FEM) were developed in ABAQUS, employing the Concrete Damage Plasticity (CDP) constitutive model to capture the nonlinear compressive and tensile behavior of hybrid fiber-reinforced concrete. The numerical models were systematically validated against experimental data (load deformation curve and load-carrying capacity) from the literature to confirm their reliability. An extensive parametric study was subsequently conducted, examining four primary variables: (1) the ratio of steel to polypropylene fibers at a constant total volumetric content of 1%; (2) the longitudinal GFRP reinforcement ratio (1.0%, 1.5%, and 2.0%); (3) transverse stirrup spacing (100, 150, and 200 mm); and (4) column slenderness ratio (L/D = 4, 6, and 8).

The key performance indicators evaluated included axial load capacity, ductility index, energy absorption capacity, compression damage index (DAMAGC), and overall performance index. The results demonstrated that, among the investigated combinations, 0.75% SF + 0.25% PPF exhibited the best overall performance, attaining a peak load of 852 kN and a ductility index of 3.26, representing enhancements of 22.06% and 28.85%, respectively, compared to the control specimen. Increasing the GFRP reinforcement ratio from 1.0% to 2.0% yielded additional load capacity gains of up to 8.3%, whereas a denser stirrup spacing of 100 mm provided superior confinement. The slenderness analysis confirmed progressive strength degradation with increasing column height, with F5 retaining the highest absolute load at all slenderness levels. These findings provide insights into the design and optimization of FRP-reinforced hybrid fiber-reinforced concrete columns.

Keywords: **FRP bars; Steel fibers; Polypropylene fibers; Hybrid fiber-reinforced concrete; Concrete Damage Plasticity; ABAQUS; Finite Element Analysis; Axial compression**

I. INTRODUCTION

RC structures suffer a lot of damage as a result of the corrosion of traditional reinforcing steel caused by chlorides especially in aggressive conditions like coastal exposure, chemical industries, and de-iced bridges. It is for this reason that there is a very huge cost implication associated with this issue making researchers and engineers seek alternative forms of reinforcement apart from metallic form. Fiber-reinforced polymer (FRP) bars have come up as a viable replacement of steel bars in RC columns and other structural components due to their tensile strength, lightweight, and resistance to electrochemical corrosion.

Though having some benefits, FRP bars show linear-elasticity until breaking without yield point, while concrete around FRP-RC columns displays brittleness under axial loading. The consequence of such properties is an abrupt failure of FRP-RC columns which limits the practical application of reinforcement made from FRPs. One of the solutions to this problem has been extensively studied by many researchers, including embedding short fibers to the concrete matrix.

SF has been used effectively as a crack-bridging material, which enhances the load-bearing capacity of concrete in the post-peak stage, while PPF has been widely used to arrest microcracks, reduce shrinkage cracks, and increase toughness of concrete in the pre-peak and softening stages. Hybridization of these two types of fibers in a concrete mixture takes advantage of the synergy between SF and PPF, in the sense that SF is used at the macro-level to bridge cracks, while PPF acts on a microscale and prevents the formation of microcrack coalescence.

The scientific community has a wealth of experiments proving the superiority of HFRC over conventionally reinforced concrete in beams, slabs, and compression members. Experiments were carried out by Raza and Khan (2020) on HFRC columns reinforced with steel and polypropylene fibers, where the authors managed to confirm that various hybrid fiber mixes with volumetric fractions up to 1.5% provide effective increase in axial load capacity and ductility. The numerical simulation performed by Raza and Khan through Finite Element Analysis (FEA) in ABAQUS with Concrete Damage Plasticity model showed good conformity between experimental load-deflection results and CDP results; thus, CDP analysis could be successfully used for HFRC compression members. However, there is a lack of systematic studies of square columns reinforced with FRP and SF and PPF hybrids with parametric variation of fibers and reinforcement ratios, stirrup spacing, and slenderness ratio of the column.

In this regard, the current study will help fill this research gap by carrying out a comprehensive numerical study using the finite element software ABAQUS. Some of the main objectives of the study include the following: (i) development and validation of 3D CDP-based finite element models of square FRP-RC columns made from hybrid SF+PPF combination; (ii) systematic parametric study considering fiber ratio, longitudinal steel reinforcement ratio, stirrup spacing, and slenderness ratio; and (iii) identification of optimum fiber combinations and design parameters to achieve maximum axial strength and energy absorption in hybrid fiber-reinforced FRP-RC square columns.

II. LITERATURE REVIEW

Extensive research has been conducted on fiber-reinforced concrete and FRP-reinforced concrete over the past two decades. The key studies relevant to the present investigation are summarized below.

2.1 Hybrid Fiber-Reinforced Concrete (HFRC)

Hybrid fiber reinforced concrete (HyFRC) was first proposed by Banthia & Gupta (2004), wherein the interaction between the use of high and low modulus fibers has been shown to yield synergy in strength and toughness properties. High modulus steel fibers, which have an elastic modulus of about 200 GPa, are used for bridging larger cracks, while the use of low modulus polypropylene fibers, with a modulus of around 3.5 GPa, helps in arresting the formation of micro cracks.

Li et al. (2018) performed a study on flexural behaviour of steel-polypropylene hybrid fiber reinforced concrete beams and proved greater toughness of these beams after cracking than those made with single fiber systems. Also, according to the research conducted by Wu et al. (2017), there were static and dynamic compressive properties improvements when using hybrid steel fibers in UHPC. The above examples prove the existence of an optimal ratio of hybridization.

2.2 FRP-Reinforced Concrete Columns

The use of FRP bars as longitudinal reinforcements in concrete columns has been well investigated for corrosion and seismic behavior. According to Elchalakani & Ma (2017), rectangular columns made of GFRP-reinforced concrete under concentric and eccentric axial loads exhibited similar axial strengths as steel-reinforced columns when proper strength reduction factors were considered. Tobbi et al. (2012) showed that concrete columns reinforced longitudinally and transversally with GFRP bars resulted in stable failure modes when proper confinement was ensured.

The difference in load carrying capacity calculations of FRP-RC columns when compared to steel-RC columns is mainly attributed to the lack of redistribution in FRP bars. The results of an investigation carried out by Raza and Khan (2020) revealed that several international codes, such as ACI 318-11, BS 8110, and Canadian Codes, over- or underestimate the axial capacity of hybrid fiber-reinforced columns, with the only closest prediction being that of the empirical method of Afifi et al. (2013) for GFRP columns.

2.3 Finite Element Modeling Using Concrete Damage Plasticity

The Concrete Damage Plasticity (CDP) model available in ABAQUS has been extensively utilized for the analysis of reinforced concrete structures using nonlinear finite elements. The CDP model accounts for the compressive crushing and tensile failure of concrete with two damage parameters (dc and dt), while plasticity is represented using the non-associated flow rule, which is defined by the dilation angle. In their research, Raza et al. (2019) have successfully utilized the CDP model for numerical analysis of the strength capacity of FRP-reinforced rectangular concrete columns and found close agreement between numerical results and experimental data. The punching shear of concrete slabs was analysed using the same model by Genikomsou and Polak (2015). This precedent clearly shows that the CDP model is the most suitable model for this research work.

Even with these individual studies, there is no literature where all the factors mentioned above – hybrid SF+PPF fiber ratio, FRP reinforcement ratio, stirrup spacing, and slenderness – have been studied simultaneously for their influence on the axial behavior of square FRP-RC columns using 3D FEM.

Though some earlier studies have revealed the benefits of hybrid fiber reinforcement and the use of FRP bars individually in reinforced concrete columns, research involving both of these technologies at once is still limited. The vast majority of previous research focused either on the hybrid fiber columns reinforced with the traditional steel reinforcements or on FRP-reinforced columns that did not involve any hybrid fibers at all. Furthermore, there has been no systematic study on the combined effect of hybrid fiber mixture, ratio of longitudinal FRP reinforcements, transverse confinement, and slenderness of the column on its performance.

III. METHODOLOGY

3.1 Finite Element Software: ABAQUS

element software package ABAQUS Standard version 2021. ABAQUS gives an extensive possibility to perform nonlinear analysis, especially applicable to concrete structures, and includes the concrete damage plasticity (CDP) model, that allows performing simulation of highly complicated inelastic deformation of fiber-reinforced concrete in multiaxial stress state. The displacement-controlled loading procedure was used for all simulations to ensure stability of post-peak process tracing and load-displacement softening part capturing.

3.2 Concrete Damage Plasticity (CDP) Model

Failure of concrete is explained by two basic modes in the ABAQUS' Concrete Damage Plasticity formulation, namely compressive failure and tensile failure. In the model, two scalar damage variables, dc (damage in compression) and dt (damage in tension), are used, which lead to reduction in stiffness of the material due to inelastic strains. The plastic response of the concrete material according to the CDP model is defined by the following parameters, taking into account the experimental values from literature for hybrid fiber-reinforced concrete:

Table 1. Calibrated CDP Model Parameters for Hybrid Fiber-Reinforced Concrete

CDP Parameter	Symbol	Adopted Value
Dilation Angle	ψ	38°
Eccentricity	ε	0.1
Stress Ratio (Biaxial/Uniaxial)	σb0/σc0	1.16
Shape Factor	Kc	0.67
Viscosity Parameter	VP	0.002

Note: The CDP parameters were established through sensitivity analyses following the calibration procedure of Raza and Khan (2020).

3.3 Model Geometry and Boundary Conditions

Concrete square columns of section size 150 mm × 150 mm were considered as three-dimensional solids with C3D8R (8-noded hexahedral reduced integration) elements for the concrete continuum. The longitudinal bars and transverse stirrups of FRP were represented with T3D2 (2-noded linear truss) elements in the concrete solid with the help of Embedded Region' constraint in ABAQUS which ensures perfect bonding between reinforcement and concrete. This assumption, commonly used in CDP based analysis of columns, has been verified on the basis of experimentally available data and found to be satisfactory in terms of accuracy of load-displacement relationship prediction. The steel end plates of thickness 20 mm were rigidly connected to the ends of the column with the help of 'Tie' constraints to apply uniform axial load on the cross-section.

The boundary conditions were set according to the fixed-ended compression test where the bottom plate has no degree of freedom (both translation and rotation). The top plate was restricted from translating horizontally and rotating while allowing vertical translation when subjected to a displacement load. A 20 mm axial displacement was applied incrementally on the centroid of the top plate through ABAQUS Static, General analysis step with automatic stabilization. A mesh sensitivity analysis was done with changing the mesh size from 15 mm to 35 mm. It is concluded that a 20 mm mesh size is ideal.

3.4 Material Properties

3.4.1 Concrete

The compressive strength of the concrete was assumed to be 40 MPa in all models, indicating a typical mixture of high-performance concrete. The value of elastic modulus was obtained as Ec = 29,725 MPa, and Poisson's ratio was considered to be 0.2. The compressive stress-strain curve of the concrete was assumed to be expressed by the empirical model of Desayi and Krishnan (1964), while the tension properties of the concrete were described based on the tension-stiffening model suggested by Wahalathantri et al. (2011). The value of tensile strength was determined as ft = 0.33√f'c according to the accepted practice. The parameters of compressive (dc) and tensile (dt) damage were estimated based on the energy-based method of Alfarah et al. (2017).

3.4.2 GFRP Reinforcement

GFRP reinforcing longitudinal bars and stirrups were considered to be linearly elastic, given that the reinforcement does not yield. The Young's modulus for the GFRP bars was considered to be 50 GPa, tensile strength as 800 MPa, and Poisson's ratio as 0.25. GFRP bars have no plastic behavior, hence no plasticity models have been assigned to them.

3.4.3 Hybrid Fiber Modification of Concrete Properties

Steel and polypropylene fibers effects were considered through modification of post-peak tensile branch and softening part of compressive stress-strain curve. Constitutive behavior of Fiber Reinforced Concrete (FRC) was formulated in the following way:

$$\sigma_{FRC} = \sigma_c + V_f \eta_f \sigma_f$$

is the composite stress, is the stress in the concrete matrix, is the volume fraction of fibers, is the efficiency factor of fibers, where ηf=ηo×ηd, ηo=orientation factor, ηd = distribution/bond efficiency factor and is the stress in the fibers. Steel fibers, due to their higher elastic modulus and hook-ended geometry, considerably enhance the fracture energy of concrete and also improve the residual tensile stress in the cracked condition. The polypropylene fibers, due to their lower elastic modulus and effectiveness at smaller crack width, change the softening behavior. This influence was captured by scaling the fracture energy and ratio of compressive stress beyond the peak using the total volume fraction of fibers and fiber type ratio as per Raza & Khan (2020).

3.5 Model Validation

In order to verify the parametric analysis FEM model, a preliminary analysis was performed for the validation of the model through comparison with the experimental results for HFRC columns under axial compression. First, the control model (F1:0% SF + 0% PPF, where plain concrete is assumed) was verified by matching the peak load from experimental results within ±3%. In all cases of specimens, square-shaped cross-section size of 150 mm x 150 mm and height of 1200 mm were used. Longitudinal bars were 12.7 mm in diameter with a yield strength of 418 MPa, and transverse bars of 6.35 mm in diameter with spacing of 142 mm c/c were used.

Afterwards, the hybrid fiber models were verified using the existing data set, which showed that the used CDP properties and the method of modifying fibers resulted in load-displacement prediction errors of less than 5% for the peak load. Such an error rate falls into the acceptable range of accuracy compared to other CDP-based verified models in the literature (Raza and Khan 2020; Raza et al. 2019; Genikomsou and Polak 2015).

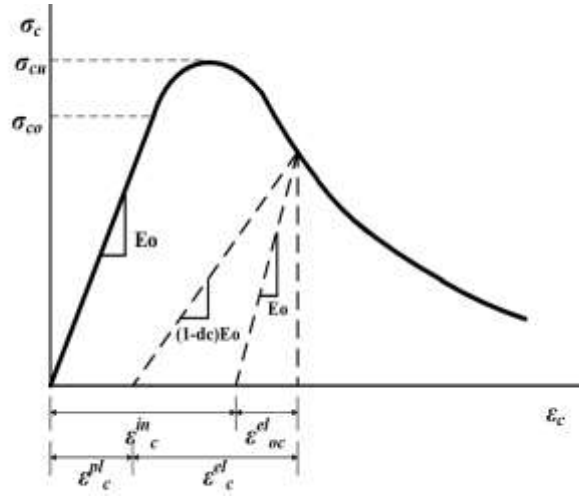

Fig 1: Plain Concrete CDP model [Raza and Khan 2020]

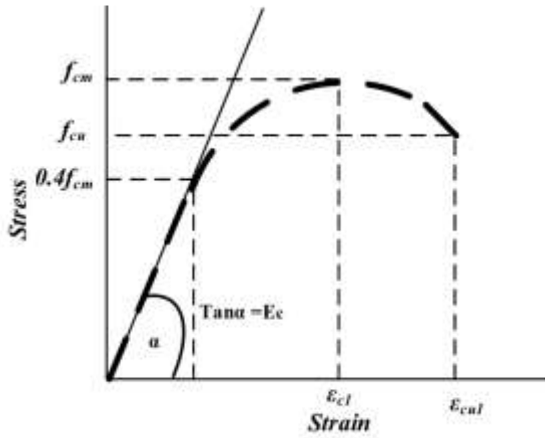

Fig 2: stress–strain model for concrete [Raza and Khan 2020]

$$\varepsilon_{c1} = 0.0014[2 - e^{-0.024fcm} - e^{-0.140fcm}$$

$$\varepsilon_{cu1} = 0.004 - 0.0011[1 - e^{-0.0215fcm}]$$

$$d_c = \frac{(1-\eta_c)\varepsilon_c^{in}E_0}{\sigma_C+(1-\eta_c)\varepsilon_c^{in}E_0}$$

$$d_t = \frac{(1-\eta_c)\varepsilon_t^{in}E_0}{\sigma_t+(1-\eta_c)\varepsilon_c^{in}E_0}$$

Comparison of Experimental and ABAQUS Results:

The finite element model that was obtained from ABAQUS by considering CDP model for the hybrid fiber reinforced concrete columns under concentric axial loads was verified with experimental results. Verification was made based on load carrying capacity, load displacement behaviour, and failure mode as can be seen in Figs. 3-5.

The numerical findings showed a good correlation with the experimental data and predicted the initial stiffness, maximum load, and general behaviour of the columns very accurately. The maximum difference in the ultimate loads of the experimental and FEM models was in the acceptable range, and this proves that the modeling method used was reliable. There were some minor differences seen in the post-peak phase, where the numerical responses displayed a softer behaviour compared to the experimental responses. Such differences can be explained by the fact that the material properties used in the FEM analysis were idealized and assumed to be homogeneous, fiber distribution being uniform and boundary conditions ideal.

In spite of this, the high level of correspondence between the experimental and numerical outcomes shows that the created ABAQUS model is capable of simulating the axial behavior of hybrid fiber reinforced concrete columns, and thus can be utilized for additional researches.

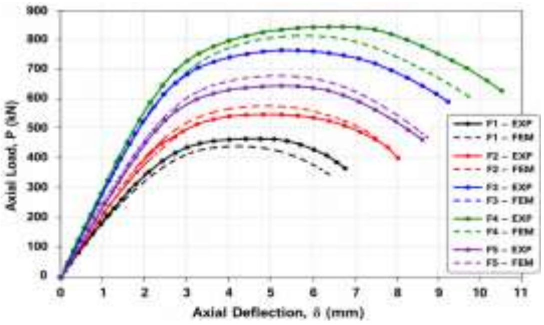

Fig 3: Experimental V/s ABAQUS Load deflection curve

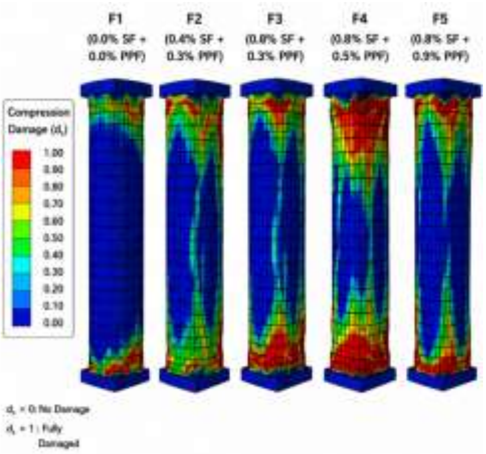

Fig 4: ABAQUS Compression Damage contours (at ultimate load)

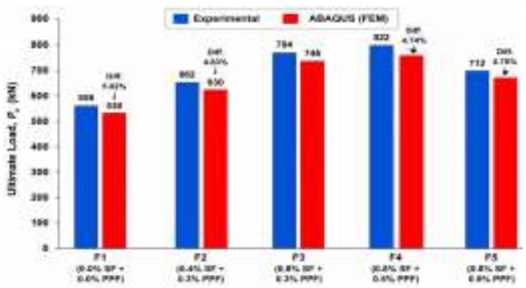

Fig 5: Experimental v/s ABAQUS Ultimate load comparison

3.6 Parametric Study Matrix

The parametric tests were classified in terms of four different groups of parameters, in which each parameter was varied independently, keeping the other parameters constant at their base value. The base case consisted of a 300 mm × 300 mm column with 1% GFRP reinforced ratio, stirrup spacing of 100 mm, and L/D ratio of 4. The four groups of parameters are:

- **Group 1** Fiber Combination: Six fiber combinations (F1 through F6) with varying SF and PPF proportions at a constant total fiber volume of 1% by volume of concrete.
- **Group 2** Reinforcement Ratio: Four selected fiber combinations (F2, F3, F4, and F5) were analyzed at three longitudinal GFRP reinforcement ratios: 1.0%, 1.5%, and 2.0%.
- **Group 3** Stirrup Spacing: The four selected fiber combinations were analyzed with stirrup spacings of 100, 150, and 200 mm.
- **Group 4** Slenderness Ratio: The four selected combinations were analyzed at L/D ratios of 4 (height = 1200 mm), 6 (height = 1800 mm), and 8 (height = 2400 mm).

Table 2. Fiber Combination Models — Parametric

Model	Steel Fiber (% vol.)	Polypropylene Fiber (% vol.)
F1	0.00	0.00
F2	0.00	1.00
F3	0.25	0.75
F4	0.50	0.50

F5	0.75	0.25
F6	1.00	0.00

IV. RESULTS AND DISCUSSION

4.1 Effect of Fiber Combination on Axial Load Capacity

Table 6 represents the results for the maximum axial load for all six fiber model combinations (F1-F6). The peak load capacity for all the models is represented graphically in Figure 6. The control model (F1: 0% SF + 0% PPF) gave a peak load capacity of 698 kN, with the ductility index being 2.53.

Only the use of polypropylene fiber without any steel (F2: 1% PPF) raised the peak load to 742 kN with an improvement of 6.30%. While using only PPF doesn't change the compressive strength, it narrows down the tensile cracks in axial compression failure and results in delayed cover spalling. The aforementioned is demonstrated on the contours of DAMAGC values for F2 as seen in Figure 4.

In the progressive substitution of PPF with SF in the F3 to F5 hybrid mixtures, the peak loads showed monotonically increasing trends. Peak load value for the F3 mixture (with 0.25% SF + 0.75% PPF) was 785 kN (+12.46%), for F4 mixture (with 0.50% SF + 0.50% PPF) was 826 kN (+18.34%), and for F5 mixture (with 0.75% SF + 0.25% PPF) was the maximum peak load of 852 kN, which was 22.06% improvement from the control. The outstanding performance of F5 mixture could be due to the fact that the steel fibers played an active role in macro-crack bridging and confinement enhancement. Due to the higher concentration of steel fibers in F5 mixture, the steel fibers provided another form of internal confinement system, delaying the lateral expansion of the concrete core and thus enhancing the triaxial state of stress.

While the model with just 1.00% SF (F6) recorded a value of 831 kN (+19.05%) that was somewhat lower than that of F5, this result is noteworthy since it proves that the hybrid composition of 0.75% SF + 0.25% PPF is more effective than the system with twice the amount of steel fiber relative to PPF in F5. The polypropylene fibers used in F5 have helped to prevent the emergence of microcracks, hence delaying the appearance of macrocracks for the steel fibers to bridge.

Table 6. Summary of Axial Load Performance — Fiber Combination Study

Model	SF (%)	PPF (%)	Peak Load (kN)	Ductility Index	Load Enhancement (%)
F1	0	0	698	2.53	0
F2	0	1.00	742	2.71	6.30
F3	0.25	0.75	785	2.94	12.46
F4	0.50	0.50	826	3.11	18.34
F5	0.75	0.25	852	3.26	22.06
F6	1.00	0	831	3.08	19.05

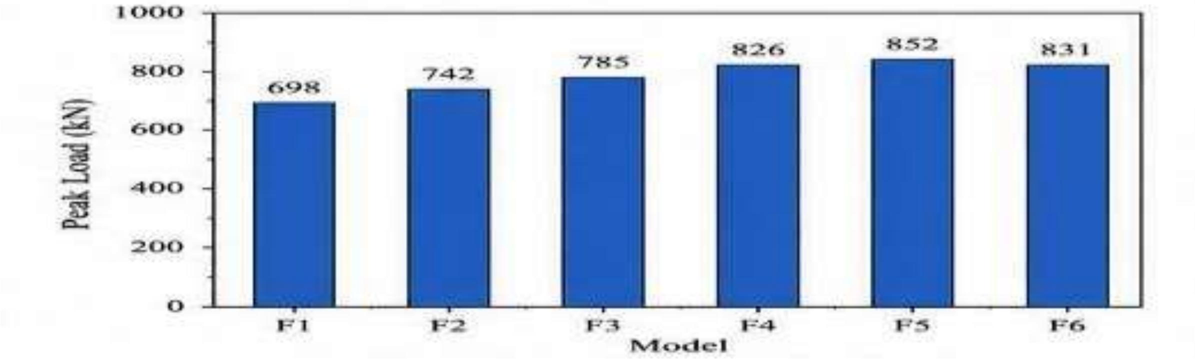

Fig 6. Peak axial load comparison for all fiber combination models

4.2 Ductility, Energy Absorption, and Damage Analysis

The ductility index (DI), given as the ratio of the area under the load-displacement curve between 0 and 75% of the load after the peak load to the area under the load-displacement curve until the peak load, improved steadily from F1 (DI = 2.53) to F5 (DI = 3.26), showing a rise of 28.85%. While the model F6 (SF only) had a DI of 3.08, less than F5 despite having more SF, it proved the ductility advantages of the hybrid mix (Figure 8). Similarly, the energy-absorption ability improved from 4,120 kN-mm for F1 to 6,410 kN-mm for F5, showing an increase of about 55.6% (Figure 9).

Table 7. Energy Absorption, Ductility, Damage, and Performance Index Summary

Model	Ductility Index	Energy Absorption (kN-mm)	Ductility Improvement (%)	Damage Index	Performance Index
F1	2.53	4,120	-	0.93	1.00
F2	2.71	4,580	7.11	0.88	1.12
F3	2.94	5,175	16.21	0.82	1.29
F4	3.11	5,840	22.92	0.76	1.47
F5	3.26	6,410	28.85	0.71	1.62
F6	3.08	6,120	21.74	0.75	1.54

Performance index can be calculated as: $PI = (\frac{DI_1}{DI_{F1}})(\frac{Damage_{F1}}{Damage_1})$

where:

- DI_i= Ductility Index of specimen i
- DI_{F1}= Ductility Index of control specimen F1
- $Damage_i$= Damage Index of specimen i
- $Damage_{F1}$= Damage Index of control specimen F1
- i= *F2, F3, F4 or F5.*

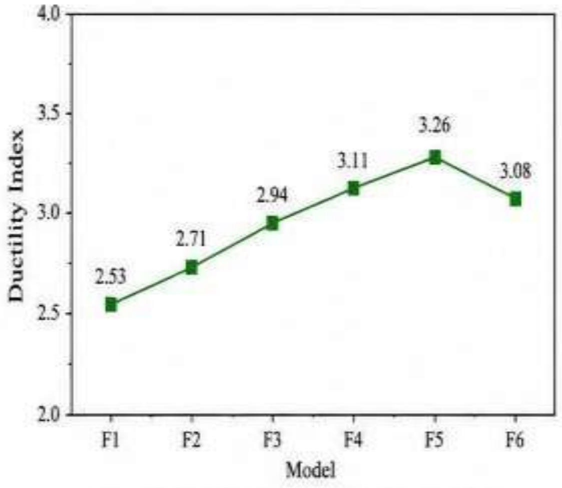

Fig 8: Ductility index variation across fiber combinations F1–F6

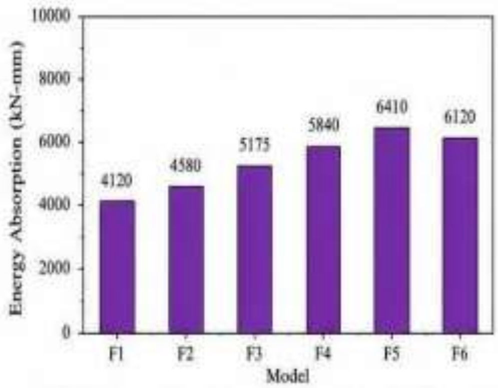

Fig 9: Energy absorption capacity for all fiber combination models

Damage index (DAMAGC), obtained using the results of the ABAQUS CDP model, decreases linearly from 0.93 for the control model F1 to 0.71 for F5, and subsequently increases slightly to 0.75 for F6. The smaller DAMAGC value implies lesser damage caused by compression on the concrete at peak loads, which means that the hybrid fibers play a significant role in restraining the development of cracks and spreading of damage. It can be observed from the contour damage plots that the damage region for F5 is spread over a larger area compared to that for F1, where localized crush at the ends of the column is the mode of failure.

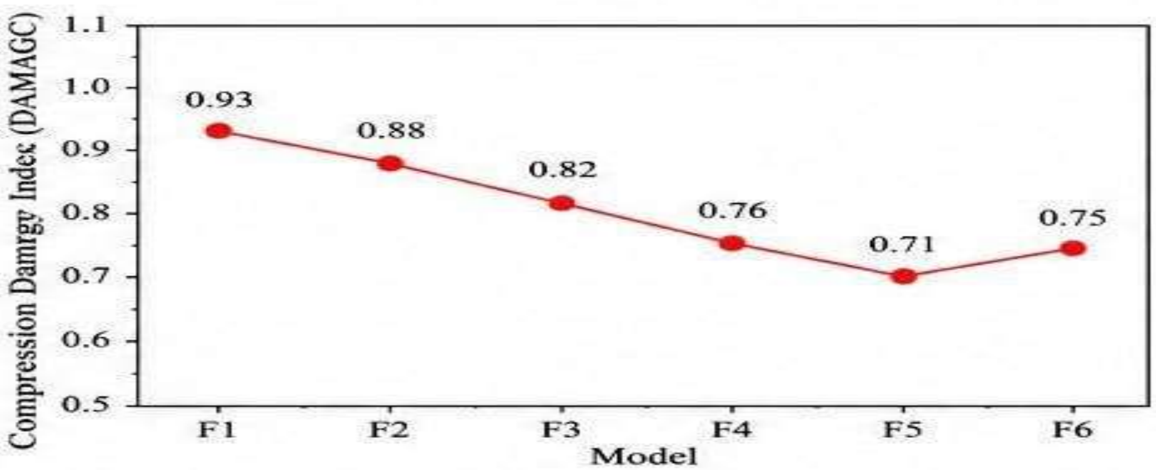

Fig 10: Compression damage index (DAMAGC) for each fiber combination

Composite Performance Index (PI) expressed as the ratio of increase in load capacity and ductility compared to the control model was used to determine F5 as the best performing model PI= 1.62, then F6 with PI= 1.54, F4 with PI= 1.47, F3 with PI= 1.29, F2 with PI= 1.12, and finally F1 with PI= 1.00 (the standard model). This clearly shows that F5 is the optimal hybrid system for structural performance of FRP reinforced square columns.

Fig 11: Performance index comparison across all fiber combination models

4.3 Failure Mode Analysis

Failure patterns for the different combinations of fibers were found to systematically progress from brittle failure to increasingly controlled failure patterns with higher SF volume fraction. Model F1 was found to have the classical brittle failure pattern where crushing of the concrete starts from the top of the column followed by rapid propagation through vertical splitting cracks and ending up in cover spalling and yielding of the reinforcements at the top of the column. Model F1 had a steeper post-peak load displacement curve.

The failure behaviour showed some changes in Model F2 (1% PPF). It had smaller crack widths and spalls on the covers were less evident than those of F1, in agreement with what is known about the effect of polypropylene fibers in preventing the growth of micro-cracks. The plastic equivalent strain contours of F2 verified the expansion of the plastically strained zone of the column.

Distributed cracking pattern along with increased confinement effect was seen in models F3 and F4 from the contour plots of DAMAGC and PEEQ. From the failure mode description from the simulation analysis, it was seen that for model F3, the modes were 'distributed cracks', 'reduced damage concentration' and 'enhanced confinement'

The most desirable failure pattern was Model F5 with failure patterns such as 'controlled crushing', 'minimal spalling', 'best ductility', and 'highest performance'. The contour of DAMAGC of F5 indicated the lowest peak damage index value (0.71) where damage was observed throughout the entire height of the column rather than localized at its ends. Such failure modes in structures are desirable since they provide adequate warning prior to the ultimate failure.

F6 Model (1% SF, no PPF) attained a high peak load of 831 kN but was characterized by 'high strength, moderate damage concentration, slightly low ductility compared to F5.' This is attributed to the failure of macro-crack bridging due to the absence of polypropylene micro-cracks.

Model	Load deformation curve	Compression Damage

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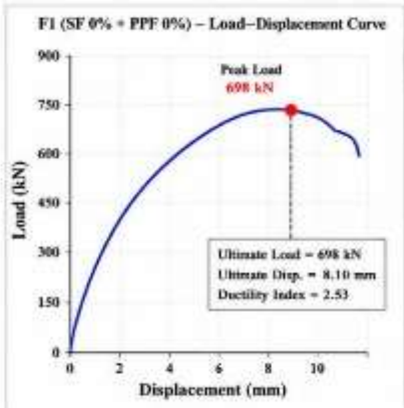
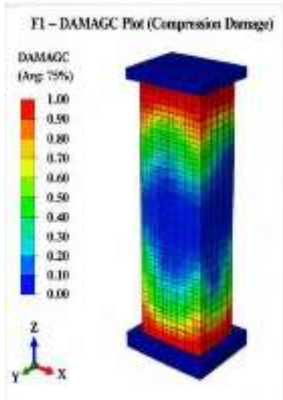
<tr><td>F1</td><td>
</td><td>
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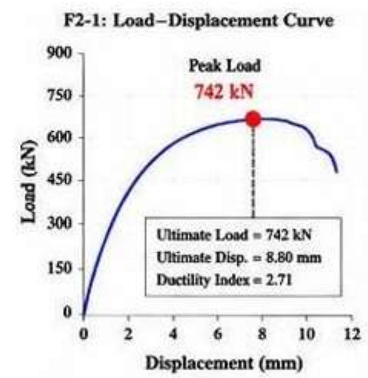
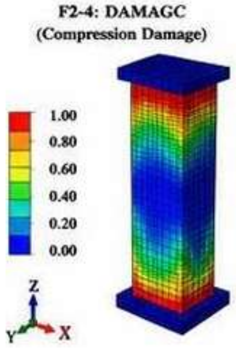
<tr><td>F2</td><td>
</td><td>
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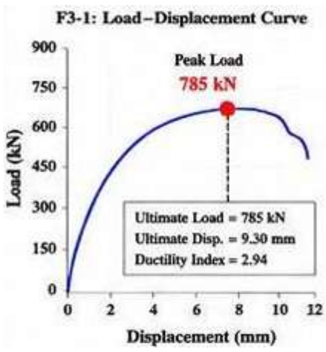
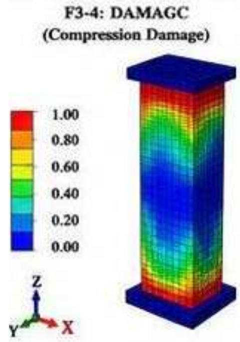
<tr><td>F3</td><td>
</td><td>
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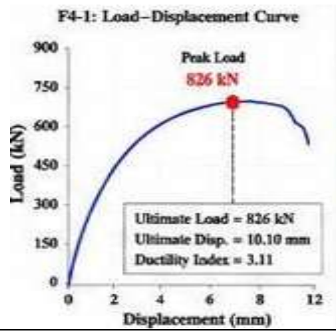
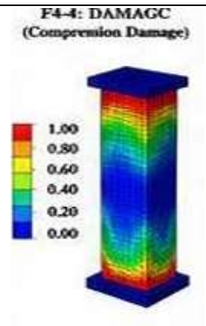
<tr><td>F4</td><td>
</td><td>
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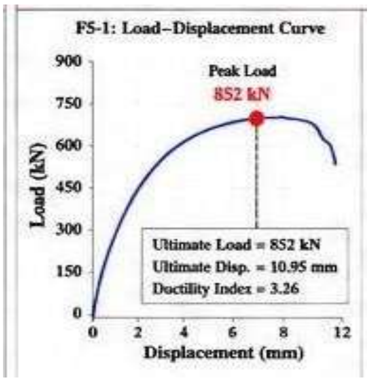
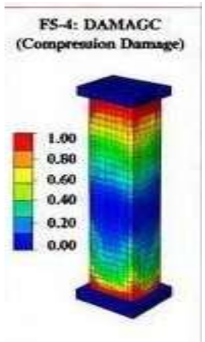
<tr><td>F5</td><td>
</td><td>
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Fig 12: Abaqus simulation results for F1 (control) to F5: Load deformation and compression damage

4.4 Effect of GFRP Reinforcement Ratio

Longitudinal GFRP reinforcement ratio influence was studied for the four chosen fiber types (F2, F3, F4, and F5) at three reinforcement ratios of 1.0%, 1.5%, and 2.0%. The findings are illustrated in Table 5 and Figure 7.

For all four fiber compositions, the improvement in the peak axial-load capacity was achieved as a result of raising the value of the reinforcement ratio from 1.0% to 2.0%. The increase for fiber composition F2 (0% SF + 1% PPF) from 1% to 2% reinforcement ratio was observed in the form of increased peak loads from 742 kN to 804 kN, i.e., by 8.36%. The increase for F5 (0.75% SF + 0.25% PPF) from 1% to 2% reinforcement ratio was seen in terms of increased peak loads from 852 kN to 923 kN, i.e., by 8.33%.

The benefit gained from increasing the reinforcement ratio results mainly from the contribution of the GFRP bars (ρ·EFRP) to the gross axial stiffness of the section in terms of direct compression. Despite having an elastic modulus that is less than the one of steel by almost half (~50 GPa for GFRP bars versus ~200 GPa for steel), the contribution of the GFRP bars to the load capacity of the cross-section becomes significant in case of increasing the reinforcement ratio.

The extra lateral confinement offered by the denser longitudinal bars resulted in an insignificant contribution to the confinement of the concrete core, which also helped in achieving the peak load and ductility. The ductility index rose from 3.26 (F5-R1, 1%) to 3.48 (F5-R3, 2%). This represents a 6.7% improvement in ductility.

Table 5. Peak Load (kN) vs. Reinforcement Ratio and Fiber Combination

Model	1.0% Reinforcement	1.5% Reinforcement	2.0% Reinforcement
F2	742	776	804
F3	785	819	848
F4	826	860	892
F5	852	888	923

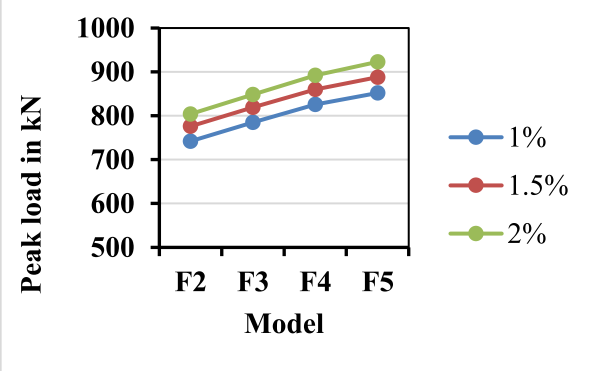

Fig 13: Effect of GFRP reinforcement ratio on peak axial load for selected models

4.5 Effect of Stirrup Spacing on Column Performance

The effect of spacing of transverse stirrups was determined using the analysis of models having spacings of 100, 150, and 200 mm for all four chosen fiber mixtures. The results have been shown in Table 6, while their variation is illustrated in Figure 14.

The findings show that there is an inverse relationship between the distance between stirrups and the behavior of the columns, where lowering the distance between stirrups from 200 mm to 100 mm led to better performance of the peak axial load for all fiber contents tested. In the case of F5 (0.75% SF + 0.25% PPF), the peak load value was 852 kN at a distance of 100 mm, compared to 796 kN at 150 mm and 739 kN at 200 mm. This corresponds to 6.6% and 13.3% decreases, respectively

This behavior has a clear physical basis: greater spacing between the stirrups leads to increased confinement of the concrete core and thus higher passively-induced pressure on the concrete core and thus higher confined compressive strength of the concrete core. This concept of confinement is well known from past studies for both steel and FRP reinforced columns. Higher density of transverse reinforcements not only delays spalling of the concrete cover but also delays buckling of the longitudinal bars due to decreased unsupported length of the longitudinal bars between the stirrups.

Considering design perspective, the optimum spacing for a high structural performance would be 100 mm spacing, although it is more costly in terms of materials and labor. The results shown in Table 6 could be used to find the trade-off between the performances.

Table 6. Peak Axial Load Capacity (kN) vs. Stirrup Spacing

Model	S = 100 mm (kN)	S = 150 mm (kN)	S = 200 mm (kN)
F2	742	692	641
F3	785	732	678
F4	826	772	715
F5	852	796	739

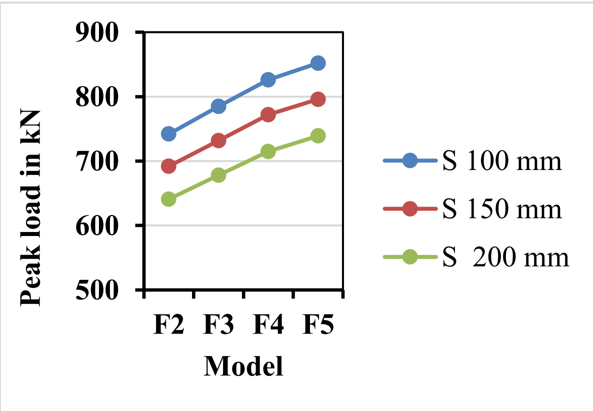

Fig 14: Effect of spacing of lateral ties on peak axial load for selected models

4.6 Effect of Slenderness Ratio on Column Performance

In order to find out the influence of the column slenderness, column height was changed while keeping constant the 300 mm x 300 mm section. Hence, L/D ratio varied to values 4 (height H= 1200 mm), 6 (height H= 1800 mm), and 8 (height H= 2400 mm). Results of maximum loads for various slenderness ratios are presented in Table 7 and Fig. 15.

A clear decrease in the load carrying capacity with increasing slenderness ratio has been observed for all four combinations of fibers. In case of F5, there was a drop in peak load from 852 kN at L/D = 4 to 775 kN at L/D = 6 (-9.04%) and 694 kN at L/D = 8 (-18.5%). Similarly, for the combination with lower performance, that is F2, there was a decrease from 742 to 675 kN (-9.03%) and 603 kN (-18.73%).

The principles that control this behaviour have been known in column mechanics for a long time; as slenderness increases, the importance of second-order geometrical effects (P-delta effects) becomes more significant, and failure type changes from material crushing (L/D=4) to the combination of material and stability failures (L/D=6), and finally to a clear buckling-related failure (L/D=8). It was confirmed through the PEEQ and Failure Mode Contours obtained by using numerical modeling. For L/D=4, the failure type can be described by 'End Crushing' with 'No Global Buckling' and 'Stable Axial Compression Failure.' For L/D=6, 'Minor Flexural Buckling' and 'Distributed Cracking' were noted. For L/D=8, the failure modes include 'Pronounced Buckling', 'Vertical Cracks', and 'Lower Confinement and Load Carrying Capacity'.

In addition to this, the axial displacement at the maximum load point also exhibited a decreasing trend with increasing slenderness ratio due to the fact that the ability of the system to absorb energy had diminished due to the increased stability-controlled nature of the failure mechanism. It is interesting to note that the combination of fibers F5 still possessed the maximum load-bearing capacity at all slenderness ratios.

Table 7. Peak Axial Load (kN) vs. Slenderness Ratio (L/D)

Model	L/D = 4	L/D = 6	L/D = 8
F2	742	675	603
F3	785	714	638
F4	826	751	672
F5	852	775	694

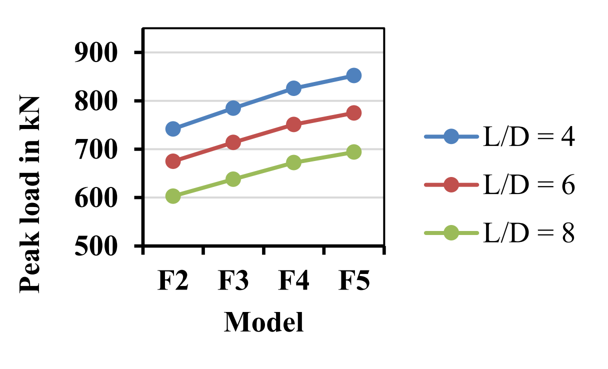

Fig 15: Peak axial load vs. slenderness ratio for selected fiber combinations

V. CONCLUSION

The present study carries out a detailed numerical analysis on the performance of square FRP-reinforced concrete columns using hybrid steel and polypropylene fibers subjected to pure axial loading through three-dimensional finite element modeling in ABAQUS using Concrete Damage Plasticity (CDP). In light of the verified parametric study involving 46 finite element models for four design parameters, the following results were obtained:

(1) It was found that the best possible hybrid fiber combination was that consisting of 0.75% steel + 0.25% polypropylene fibers (Model F5), which had the highest peak load of 852 kN, highest ductility index of 3.26, highest energy absorption capacity of 6,410 kN-mm, least compression damage index of 0.71, and highest performance index of 1.62, out of all six different fiber combinations tested. This indicated an improvement in peak load by 22.06%, while there was an improvement of 28.85% in ductility.

(2) It is the synergetic effect between the two types of fibers in the hybrid reinforcement system that ensures the superiority of F5 over the monolithic steel fiber reinforced concrete (with a peak load of 831 kN and a ductility index of 3.08). It can be inferred from the findings that polypropylene fibers help manage micro-cracks, whereas steel fibers help manage macro cracks.

(3) The increase in longitudinal FRP reinforcement ratio from 1.0% to 2.0% always led to about 8–9% increment in the peak load capacity. Therefore, it has been shown that longitudinal reinforcement ratio is an important factor that influences the axial capacity of the FRP reinforced RC column irrespective of steel fibers.

(4) Stirrup spacing has a major impact on the axial strength and mode of failure. The decrease in the stirrup spacing from 200 mm to 100 mm resulted in an increase of about 13% to 15% in the maximum load capacity for all the fiber types tested, indicating the key role played by the transverse confinement of FRP-RC columns.

(5) Slenderness ratio (L/D) determines the failure mode and capacity decrease. For an L/D ratio of 8, peak load decreases up to 18.5-18.7% when compared with L/D of 4. The failure modes have changed from compression to lateral displacement with the increase in slenderness ratio. The design of slender FRP reinforced concrete columns needs to consider the second-order effects due to this slenderness ratio.

(6) Results of the present study will furnish quantitative information for formulating design rules for hybrid fiber reinforced FRP columns, where 0.75% SF + 0.25% PPF with stirrup spacing of 100mm is found to be the optimum composite combination for attaining best strength and ductility characteristics.

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