

NUMERICAL INVESTIGATION OF HYBRID-FIBER-REINFORCED CONCRETE COLUMNS USING THE CONCRETE DAMAGED PLASTICITY MODEL IN ABAQUS

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Abstract

This study presents a nonlinear finite element investigation of short rectangular reinforced concrete columns incorporating hybrid steel and polypropylene fibers using the Concrete Damaged Plasticity (CDP) model implemented in ABAQUS Standard. The numerical investigation was conducted on 21 concentrically loaded column models using previously reported experimental results as the reference dataset. The modeled columns had a rectangular cross-section of 150 × 150 mm and a height of 1200 mm. The numerical framework incorporated concrete, longitudinal and transverse reinforcement, steel loading plates, contact constraints, material properties, boundary conditions, mesh discretization, and axial loading. Model calibration was performed by examining the sensitivity of the response to CDP parameters, including dilation angle, viscosity parameter, flow-potential eccentricity, and the shape factor K_{cK_c} . Following calibration, the numerical predictions were compared with experimental peak loads, axial deformation at peak load, load–deformation behavior, and crack patterns. The calibrated control specimen M-6 used a dilation angle of 42°, viscosity parameter of 0.0075, and mesh size of 40 mm. Across the 21 specimens, the ABAQUS models reproduced the experimental peak-load response with generally good agreement, although considerably larger differences occurred for axial deformation in several specimens. The results indicate that CDP-based nonlinear finite element analysis can provide a useful computational framework for examining the behavior of hybrid-fiber-reinforced concrete columns and for conducting parametric investigations that would otherwise require extensive experimental testing. The study also demonstrates that careful calibration of CDP parameters is essential for obtaining stable and representative numerical predictions.

INTRODUCTION

Concrete is one of the most widely used construction materials because of its high compressive strength, durability, availability, and versatility. Reinforced concrete columns are particularly important structural members because they transfer gravity loads from beams and slabs to foundations. However, conventional concrete has relatively limited tensile strength and is susceptible to cracking and brittle damage. The incorporation of discrete fibers into concrete is therefore an established approach for improving crack control, toughness, deformation capacity, and selected mechanical properties.

Fiber-reinforced concrete can contain steel, polypropylene, glass, carbon, or other fibers. Different fiber types perform different functions within the cementitious matrix. Steel fibers can provide bridging across larger cracks and contribute to load transfer after cracking, whereas polypropylene fibers can help control smaller cracks and improve the post-cracking response. Combining different fibers creates a hybrid-fiber-reinforced concrete (HFRC) system in which fibers with different geometries and mechanical properties can operate at different stages of cracking.

The dissertation underlying this article investigated the numerical behavior of 21 short reinforced concrete columns containing hybrid steel and polypropylene fibers. The study developed nonlinear finite element models in ABAQUS Standard and compared their predictions with previously available experimental results. The source dissertation describes the columns as concentrically loaded rectangular specimens and uses the Concrete Damaged Plasticity (CDP) model for concrete while representing reinforcing steel using a simplified linear-elastic assumption.

The use of numerical modeling is particularly valuable for reinforced concrete because full-scale experimental testing is expensive, time-consuming, and restricted by the number of variables that can practically be investigated. Finite element analysis can provide additional information concerning stress distribution,

deformation, damage development, and cracking patterns. It can also facilitate controlled parametric studies after an experimentally validated model has been established.

ABAQUS provides a CDP constitutive model specifically intended for concrete and other quasi-brittle materials. The model incorporates tensile and compressive damage, plasticity, stiffness degradation, and non-associated flow. The formulation is associated with the plastic-damage framework developed by Lee and Fenves, while the ABAQUS implementation includes parameters such as dilation angle, flow-potential eccentricity, the biaxial-to-uniaxial compressive stress ratio, KcK_c , and viscosity regularization. Previous research has demonstrated the potential of hybrid fibers to modify the mechanical and structural behavior of concrete. Vairagade and Kene investigated combinations of steel and polypropylene fibers and reported improvements in selected mechanical properties compared with plain concrete. More recent structural studies have also examined hybrid steel-polypropylene systems in columns and other structural members, supporting the relevance of hybridization for strength, ductility, cracking, and energy dissipation.

The present study therefore focuses on the numerical simulation and calibration of hybrid-fiber-reinforced concrete columns using the CDP model in ABAQUS Standard.

1.1 Research Objectives

The principal objectives were to:

To develop nonlinear finite element models of hybrid-fiber-reinforced concrete columns in ABAQUS Standard;

To calibrate important CDP parameters using the control specimen;

To investigate the influence of dilation angle, viscosity parameter, flow-potential eccentricity, and KcK_c ;

To compare numerical and experimental peak loads and axial deformations;

To examine numerical load-deformation behavior and crack patterns; and

To evaluate the suitability of the calibrated FE model for additional parametric investigation.

2. Literature Review

2.1 Hybrid-Fiber-Reinforced Concrete

Hybridization involves combining two or more fiber types within a concrete matrix. The objective is not simply to increase the quantity of fibers but to exploit complementary mechanisms. Steel fibers have relatively high stiffness and strength and can bridge larger cracks, while polypropylene fibers have lower stiffness but can provide distributed crack-control effects.

Vairagade and Kene experimentally investigated hybrid steel-polypropylene fiber-reinforced concrete and considered different combinations of the two fiber types. Their work illustrates the potential for fiber combinations to modify compressive and tensile behavior.

A later study by Vairagade and Kene examined metallic and synthetic fibers and reported improvements in compression and splitting strength for selected fiber configurations.

At the structural-member level, hybrid steel-polypropylene fiber concrete has also been investigated under axial and cyclic loading. Research on reinforced concrete columns has reported improvements in bearing capacity, deformation capacity, ductility, and energy dissipation associated with fiber incorporation, although the magnitude of improvement depends on fiber type, dosage, reinforcement ratio, loading condition, and other structural variables.

2.2 Numerical Modeling of Reinforced Concrete

Finite element analysis provides a numerical approach for solving complex structural problems by discretizing a continuous structure into finite elements. In reinforced concrete, nonlinear FE analysis is particularly useful because concrete exhibits cracking, crushing, stiffness degradation, nonlinear stress-strain behavior, and different responses in tension and compression.

The source dissertation used ABAQUS Standard to construct three-dimensional numerical models

of the columns. The modeling procedure included geometry creation, material assignment, assembly, interaction definition, loading steps, meshing, and boundary conditions.

Raza et al. demonstrated the application of nonlinear finite element analysis using CDP for rectangular reinforced concrete members and reported good agreement between numerical and experimental responses following model calibration.

2.3 Concrete Damaged Plasticity Model

The CDP model represents concrete through a combination of plasticity and damage mechanics. The model accounts for the degradation of stiffness associated with concrete cracking and crushing. ABAQUS defines the CDP model through the flow potential, yield surface and viscosity parameters, together with tensile and compressive behavior definitions.

Lee and Fenves developed a plastic-damage model incorporating separate tensile and compressive damage variables and stiffness degradation. The formulation was intended to represent different damage states of concrete and provide a computationally practical constitutive framework. The source study specifically investigated the influence of dilation angle, viscosity parameter, eccentricity and KcK_c during model calibration. The dissertation reports that changes in these parameters altered the simulated force-displacement response.

3. Materials and Numerical Methodology

3.1 Research Design

The study followed a numerical-experimental comparison framework. Experimental results from an earlier investigation were used as the reference dataset, while the present research reproduced the structural specimens computationally in ABAQUS Standard.

A total of 21 column specimens, designated M-1 to M-21, were numerically modeled. The columns were rectangular short reinforced concrete members subjected to concentric axial loading.

Table 1. Summary of the numerical research methodology

Parameter	Description
Research approach	Nonlinear numerical finite element analysis
FE software	ABAQUS Standard
Number of models	21
Model type	Short rectangular reinforced concrete columns
Cross-section	150 × 150 mm
Column height	1200 mm
Loading	Concentric axial compression
Concrete model	Concrete Damaged Plasticity
Reinforcement	Steel reinforcement
Reference data	Previously reported experimental results
Main outputs	Peak load, axial deformation, load–deformation response, crack pattern
Calibration specimen	M-6
Calibrated dilation angle	42°
Calibrated viscosity parameter	0.0075
Selected mesh size	40 mm

The geometry and principal modeling procedure are reported in the source dissertation.

3.2 Geometry and Boundary Conditions

The numerical column geometry consisted of a 150 mm × 150 mm rectangular cross-section with a height of 1200 mm. Steel loading plates were placed at the top and bottom of the column to provide load transfer and boundary support.

The dissertation describes the interaction between the steel plates and concrete assembly using ABAQUS constraints and specifies the master-slave relationship for the interacting surfaces.

The principal material and analysis parameters reported in the source are summarized in Table 2.

Table 2. Principal model and analysis parameters

Parameter	Value
Concrete density reported in dissertation	$2.40 \times 10^{-9} \text{ t/mm}^3$
Poisson's ratio	0.20
Young's modulus	4700 N/mm ²
Concrete cover	20 mm
Initial increment	0.01
Maximum increment	1
Minimum increment	10^{-9}
Maximum number of increments	10,000
Final mesh size	40 mm
Dilation angle	42°
Viscosity parameter	0.0075

3.3 Finite Element Modeling Procedure

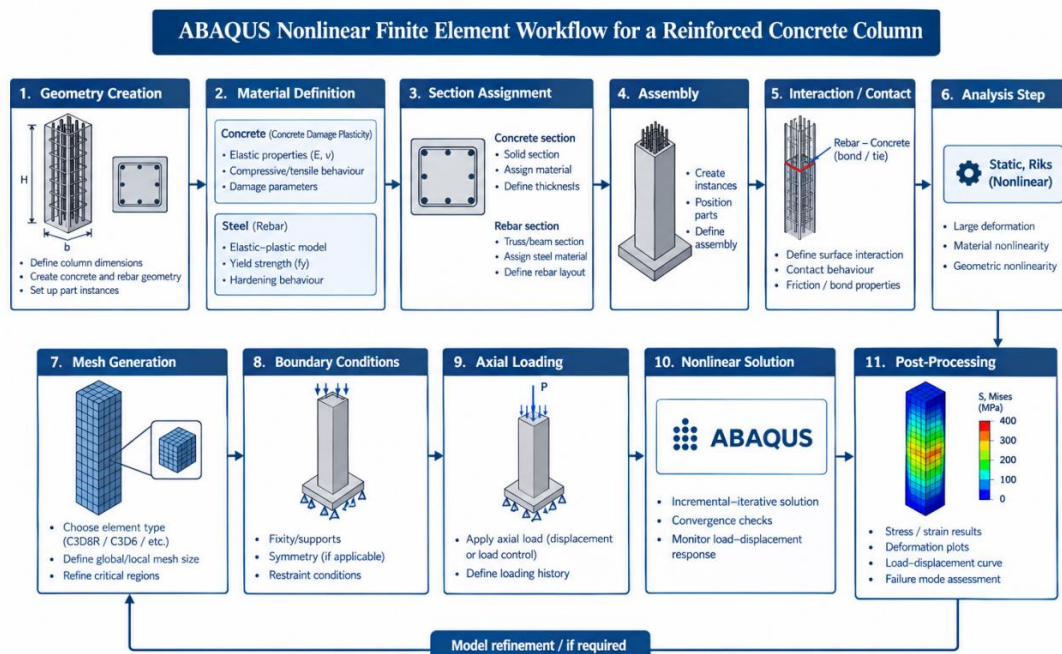
The numerical model was constructed through the standard ABAQUS workflow:

creation of the column geometry;
definition of concrete and steel material properties;

assignment of sections;
 assembly of column components;
 definition of interactions;
 creation of the nonlinear analysis step;
 mesh generation;
 application of boundary conditions and axial loading;

execution of the analysis;
 post-processing of numerical results.
 The dissertation specifically documents the parts, property, assembly, interaction, step, mesh and loading stages.

Figure 1: Finite element modeling workflow for hybrid-fiber-reinforced concrete columns.



3.4 CDP Model Calibration

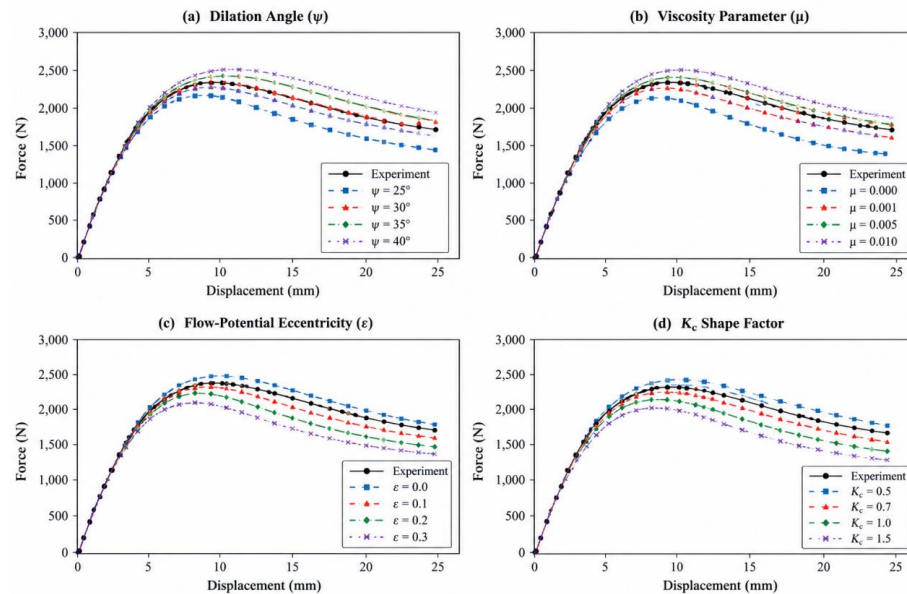
The CDP model was calibrated before the complete set of 21 models was analyzed. Four parameters were investigated: dilation angle, viscosity parameter, flow-potential eccentricity, and KcK_c .

The dilation-angle sensitivity analysis examined values including 30° , 35° , 38° , 40° , and 42° . The viscosity parameter was varied from approximately 0.003 to 0.0075. Flow-potential eccentricity was also varied, while the KcK_c

parameter was examined through several values. The final calibrated parameters selected for the control specimen M-6 were:
 dilation angle = 42° ;
 viscosity parameter = 0.0075; and
 mesh size = 40 mm.

The source dissertation reports that the numerical and experimental ultimate load and deformation of M-6 were approximately similar after calibration.

Figure 2: Sensitivity of the numerical response to key Concrete Damaged Plasticity parameters.



4

Results and Discussion

4.1 Comparison of Peak Axial Load

The numerical results for all 21 models were compared with the corresponding experimental peak loads. The source dissertation reports that the numerical models generally followed the

experimental behavior, particularly within the principal load-carrying range.

The ABAQUS peak loads ranged from 459.8 kN to 836.03 kN, whereas the corresponding experimental peak loads ranged from 415 kN to 850 kN.

Table 3. Comparison between numerical and experimental peak loads

Model	FEA peak load (kN)	Experimental peak load (kN)	Difference (%)
M-1	459.80	415	10.80
M-2	742.50	700	6.07
M-3	731.50	750	-2.47
M-4	635.60	650	-2.21
M-5	470.82	450	4.63
M-6	469.82	550	-14.58
M-7	757.38	800	-5.33
M-8	799.51	800	-0.06
M-9	836.03	850	-1.64
M-10	665.64	650	2.40
M-11	490.79	500	-1.84
M-12	622.67	550	13.21
M-13	799.37	800	-0.08
M-14	787.43	800	-1.57
M-15	527.76	600	-12.04
M-16	518.73	550	-5.69
M-17	603.72	600	0.62

M-18	800.30	850	-5.85
M-19	626.70	500	25.34
M-20	543.72	450	20.83
M-21	517.73	550	-5.87

The smallest absolute peak-load difference was observed for M-8, for which the numerical value was 799.51 kN compared with an experimental value of 800 kN. M-13 also showed a very close prediction, with 799.37 kN compared with 800 kN.

The largest positive numerical deviation occurred for M-19, where the FE prediction was 626.70 kN compared with an experimental value of 500 kN. Conversely, the largest negative difference was observed for M-6, where the numerical result was 469.82 kN compared with 550 kN.

These variations demonstrate that a calibrated CDP model can reproduce peak-load behavior reasonably well for many specimens but cannot

be assumed to reproduce every experimental response with identical accuracy.

4.2 Axial Deformation

Axial deformation at peak load showed greater discrepancies between the numerical and experimental models than peak load.

For example, M-1 produced a numerical deformation of 6.84 mm compared with an experimental value of 4.51 mm, while M-2 produced 14.33 mm numerically compared with 4.11 mm experimentally. The dissertation attributes some of the discrepancy to simplified assumptions concerning the interaction between reinforcement and concrete and the linear-elastic treatment of reinforcement.

Table 4. Selected deformation comparisons

Model	FEA deformation (mm)	Experimental deformation (mm)
M-1	6.84	4.51
M-2	14.33	4.11
M-3	13.82	6.52
M-4	10.80	8.10
M-5	6.84	12.12
M-6	7.01	7.00
M-8	16.21	9.20
M-9	19.01	7.62
M-11	7.54	7.14
M-17	9.94	9.26
M-21	8.13	12.11

The control specimen M-6 is particularly important because its numerical deformation of 7.01 mm was almost identical to the experimental value of 7.00 mm. This agreement supported the subsequent use of the calibrated model for the remaining specimens.

4.3 Load-Deformation Response

The numerical and experimental load-deformation curves generally followed similar

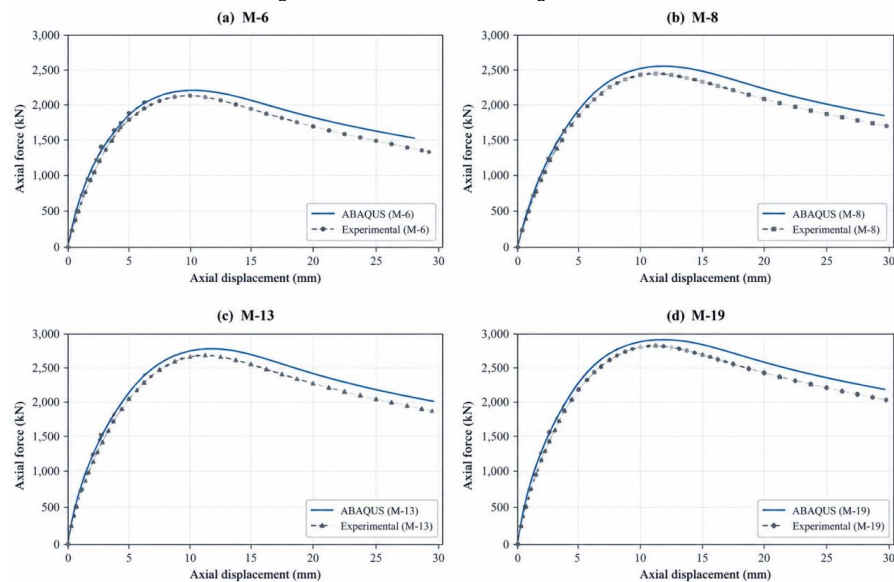
initial elastic trends. The source dissertation reports that most models showed good agreement during the elastic stage, with larger differences appearing after the onset of nonlinear behavior and near ultimate response.

This observation is consistent with the difficulty of representing concrete cracking, crushing, stiffness degradation, reinforcement interaction, and post-peak behavior through a simplified constitutive model.

The CDP model is particularly useful because it provides mechanisms for representing both tensile and compressive damage. ABAQUS documentation identifies the model as a

constitutive framework for concrete and other quasi-brittle materials and includes stiffness degradation and viscoplastic regularization.

Figure 3 Caption: Comparison of numerical and experimental load–deformation responses for representative column specimens.



4.4 Crack Patterns

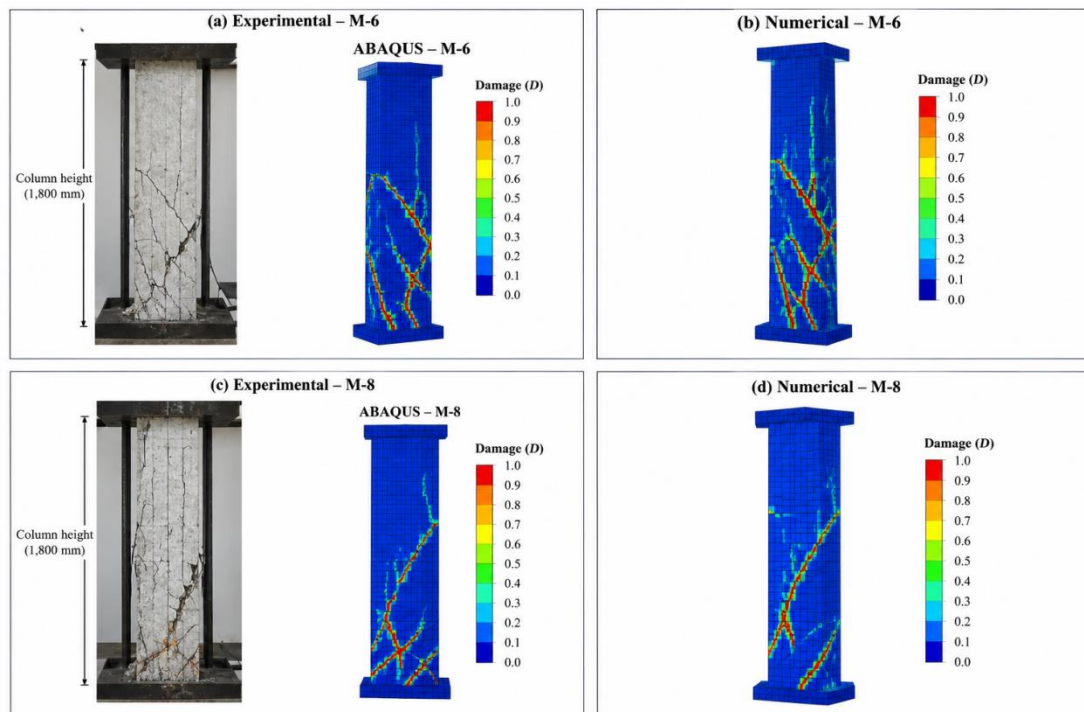
Cracking behavior was evaluated using the principal plastic strain response generated by the CDP model. The dissertation states that concrete cracking begins when the relevant principal plastic-strain criterion is reached and uses maximum principal plastic strain to visualize numerical crack patterns.

Numerical crack patterns were compared with corresponding experimental crack patterns for

the 21 specimens. The dissertation presents paired numerical and experimental crack-pattern figures from M-1 through M-21.

The comparison of crack patterns provides an additional validation criterion beyond peak load. Even where the ultimate numerical load is close to the experimental result, differences in the location, orientation, and concentration of cracks can reveal limitations in material assumptions or mesh resolution.

Figure 4: Representative numerical and experimental cracking patterns of hybrid-fiber-reinforced concrete columns.



4.5 Effect of CDP Parameters

The calibration study demonstrates that the numerical response is sensitive to constitutive parameters.

The dissertation reports that increasing the viscosity parameter from approximately 0.003 to 0.0075 changed the simulated peak response. Similarly, variations in dilation angle altered the force-displacement relationship, with 42° selected for the final M-6 model.

From a numerical mechanics perspective, this sensitivity is expected. The dilation angle influences the volumetric component of plastic flow, while the viscosity parameter provides viscoplastic regularization in ABAQUS/Standard. ABAQUS documentation notes that small viscosity values can improve convergence in softening regimes without substantially compromising the underlying response when appropriately selected.

The results therefore emphasize that CDP parameters should not be selected arbitrarily. They should be calibrated against experimental

structural response whenever reliable experimental data are available.

5. Discussion

The principal outcome of the study is that nonlinear FE modeling using the CDP model can reproduce important aspects of hybrid-fiber-reinforced concrete column behavior. The peak-load comparisons demonstrate close numerical-experimental agreement for many specimens, while the load-deformation curves provide evidence that the models can capture the principal stages of structural response.

The result for M-8 is particularly notable: the numerical peak load was 799.51 kN against an experimental value of 800 kN, representing an almost negligible difference. Similar agreement was obtained for M-13.

However, numerical accuracy was not uniform across all response variables. The axial deformation results showed substantially larger differences in several specimens. This distinction is important because a model may predict

ultimate strength accurately while still providing an imperfect representation of deformation and post-peak behavior.

One possible explanation is the simplified representation of reinforcement and reinforcement-concrete interaction. The source study assumed linear-elastic behavior for the steel reinforcement, and the authors noted that the assumption of perfect bond and the absence of reinforcement damage criteria could contribute to differences after the elastic stage.

The findings are consistent with the broader literature demonstrating that CDP-based FE models can provide useful predictions for reinforced concrete structures when the model is properly calibrated. Raza et al. similarly developed and calibrated a CDP model in ABAQUS for rectangular concrete members and reported good agreement with experimental results.

The use of hybrid fibers also has structural relevance. Experimental research has reported beneficial effects of steel-polypropylene hybrid fibers on the structural performance of reinforced concrete columns, including bearing capacity and deformation-related behavior under particular loading conditions.

At the same time, hybridization should not be interpreted as automatically producing higher capacity under every structural configuration. Recent research has shown that the contribution of steel and polypropylene fibers can differ considerably: steel fibers may contribute more directly to load resistance, while polypropylene fibers can play a stronger role in crack control and post-peak response.

Therefore, the principal contribution of the present numerical investigation is not simply the demonstration that fibers increase concrete strength, but rather the demonstration that a calibrated nonlinear FE framework can be used to investigate the structural response of hybrid-fiber columns and examine parameters that are difficult to isolate experimentally.

6. Practical Implications

The findings have several implications for structural engineering practice and research.

First, nonlinear FE analysis can reduce the number of physical experiments required during preliminary investigations. Once a model has been calibrated against reliable experimental results, additional combinations of geometry, reinforcement, fiber content, and material properties can be investigated numerically.

Second, CDP calibration should be treated as a fundamental part of the modeling process rather than a secondary numerical step. Parameters such as dilation angle and viscosity can materially influence the predicted response.

Third, peak-load validation alone is insufficient. A robust model should also be evaluated using deformation, load-deformation response, damage evolution, and crack patterns.

Fourth, the use of hybrid fibers should be investigated through controlled parametric studies rather than assuming that increasing total fiber content will continuously improve structural performance. Previous experimental evidence indicates that the effectiveness of hybridization depends on the proportions and characteristics of the constituent fibers.

7. Limitations

Several limitations should be recognized.

The numerical models were based on previously reported experimental data rather than a new experimental campaign.

The study focused on short rectangular columns subjected to concentric axial loading.

Reinforcement behavior was simplified as linear elastic in the numerical model.

Perfect or highly idealized bond behavior between reinforcement and concrete may contribute to differences in deformation and post-peak response.

The numerical study did not investigate a broad range of fiber volume fractions independently.

Mesh sensitivity was considered during calibration, but a comprehensive mesh-convergence study should be reported in a future journal version.

Some material-property and unit descriptions in the original dissertation require verification against the original experimental source before publication.

These limitations do not invalidate the numerical findings but define the range within which they should be interpreted.

8. Recommendations for Future Research

Future investigations should extend the present work in several directions.

First, the influence of transverse reinforcement spacing should be systematically investigated. The original dissertation specifically recommends studying changes in transverse reinforcement spacing and their influence on load-deformation behavior.

Second, alternative element types and mesh densities should be evaluated to determine their influence on numerical response.

Third, nonlinear reinforcement behavior should be introduced rather than assuming purely linear elasticity. Explicit reinforcement damage and yielding could improve the prediction of deformation and post-peak response.

Fourth, future studies should investigate eccentric and cyclic loading because columns in seismic regions are frequently subjected to combined axial and lateral demands. Existing research has demonstrated the relevance of hybrid steel-polypropylene fibers under cyclic column loading.

Finally, a broader parametric framework could investigate fiber dosage, fiber aspect ratio, concrete strength, reinforcement ratio, slenderness ratio, load eccentricity, and confinement simultaneously.

9. Conclusion

This study presented a nonlinear finite element investigation of 21 hybrid-fiber-reinforced concrete column models using the Concrete Damaged Plasticity model in ABAQUS Standard.

The principal conclusions are:

The calibrated ABAQUS model was able to reproduce the general axial-load response of the investigated reinforced concrete columns with

generally good agreement with experimental peak-load values.

The numerical peak loads for the 21 models ranged from 459.8 to 836.03 kN, compared with experimental values ranging from 415 to 850 kN. M-8 produced particularly close agreement, with a numerical peak load of 799.51 kN compared with an experimental value of 800 kN.

The control specimen M-6 provided a useful calibration case, with numerical and experimental deformations of approximately 7.01 and 7.00 mm, respectively.

The calibrated model used a dilation angle of 42° , viscosity parameter of 0.0075, and mesh size of 40 mm.

Peak-load prediction was generally more consistent than deformation prediction, indicating that validation should consider multiple response measures.

The numerical crack patterns provided an additional qualitative means of evaluating the FE model against experimental behavior.

The results demonstrate that CDP-based nonlinear finite element analysis can serve as an effective computational tool for investigating hybrid-fiber-reinforced concrete columns and conducting parametric studies.

The model should nevertheless be further improved through nonlinear reinforcement behavior, refined bond modeling, systematic mesh convergence, and expanded loading conditions.

Overall, the study demonstrates the value of combining experimental evidence with calibrated numerical modeling. Rather than replacing experimental investigation, ABAQUS-based nonlinear analysis can complement laboratory testing by allowing researchers to investigate structural parameters and failure mechanisms that would otherwise require extensive experimental resources.

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