Finite Element Modeling of CFRP-Reinforced and CFRP-Strengthened Concrete Beams in ABAQUS:

A Review of Modeling Practice and Reported Validation Evidence

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Abstract-*Carbon Fiber Reinforced Polymer (CFRP) bars and sheets are increasingly used as internal reinforcement or external strengthening for reinforced concrete (RC) beams, offering corrosion resistance and a high strength-to-weight ratio relative to steel. Finite element (FE) simulation in ABAQUS, typically using the Concrete Damaged Plasticity (CDP) constitutive model for concrete and linear-elastic truss or shell elements for CFRP, has become the dominant numerical tool for investigating the flexural response of such members. This paper synthesizes modeling practice and validation outcomes reported across a set of published experimental-numerical studies on CFRP-reinforced and CFRP-strengthened concrete beams, nearly all tested under four-point bending rather than pure axial loading. It summarizes the material property ranges commonly adopted for concrete and CFRP, the CDP input parameters used across studies, and the qualitative and quantitative agreement between FE predictions and laboratory measurements as reported by the original authors. Reported deviations between numerical and experimental ultimate loads are generally within roughly 10–20% when the concrete-CFRP bond and CDP dilation angle are calibrated appropriately, though larger discrepancies occur when debonding or localized cracking is not well captured by the smeared-damage CDP formulation. The review highlights consistent findings on the influence of CFRP reinforcement ratio, bar/plate length, and bond modeling on predicted capacity and stiffness, and identifies mesh sensitivity, bond-slip characterization, and post-peak softening as recurring sources of uncertainty. The paper closes with recommendations for researchers planning new FE validation studies in this area. Three models have been simulated in this study and referred as FEA1 and FEA2 with CFRP and control specimen. The results show good agreement with the test results specially the test specimen strengthened outer with CFRP sheet while the simulated specimens reinforced in bottom location with CFRP rebars.*

Keywords: CFRP; reinforced concrete beams; ABAQUS; Concrete Damaged Plasticity; finite element validation; flexural behavior; bond-slip modeling Displacement

1. INTRODUCTION

Reinforced concrete (RC) remains the most widely used structural material worldwide, but conventional steel reinforcement is vulnerable to corrosion, particularly in marine, coastal, and de-icing-salt environments, which shortens service life and increases maintenance cost. Fiber Reinforced Polymer (FRP) bars and CFRP bars specifically have been investigated since the 1990s as a corrosion-free alternative or complement to steel, owing to their high tensile strength, light weight, and non-conductivity. CFRP is also widely used externally, bonded or near-surface-mounted, to strengthen or retrofit existing RC beams that are deteriorated, damaged, or required to carry increased loads.

Because CFRP behaves in a linear-elastic manner up to brittle rupture, with no yield plateau, its use as internal reinforcement changes the failure mode, ductility, and serviceability behavior of RC beams relative to steel-reinforced members. Understanding this behavior experimentally is costly and time-consuming, which has motivated extensive use of nonlinear finite element (FE) analysis, most commonly in ABAQUS, using the Concrete Damaged Plasticity (CDP) model to represent concrete cracking and crushing, combined with elastic or orthotropic elastic representations of the CFRP reinforcement or laminate.

A large and still-growing body of published work pairs a laboratory testing program with an ABAQUS FE model calibrated or validated against the test data. This review synthesizes that literature rather than presenting a new, unpublished set of ten validation cases, because fabricating specific numerical "experimental vs. FE" load and deflection values not actually generated by a real ABAQUS run and real laboratory tests would misrepresent the work as original validated research. Instead, the aim here is to give an accurate, source-grounded account of (a) how researchers build these FE models, (b) what material property ranges and CDP parameters are typically used, and (c) what level of agreement between FE and experiment has actually been reported in the literature.

One clarification on scope: essentially all of the published experimental-numerical CFRP RC beam studies identified for this review test beams in three- or four-point bending (flexure), which is the loading configuration relevant to a beam's primary structural function. Axial loading of "beams" in the strict sense is uncommon in this literature; axial compression studies of CFRP-related members are concentrated instead on FRP-confined or FRP-reinforced columns. This paper therefore focuses on flexural loading, which is almost certainly what is structurally relevant to CFRP rebar-in-beam applications; a reader specifically interested in axial members should consult the FRP-confined column literature separately.

2. LITERATURE REVIEW

Table 1 summarizes ten representative published studies that combine laboratory testing of CFRP-reinforced or CFRP-strengthened RC beams with ABAQUS (or, in one comparative case, DIANA) finite element modeling. These are real, verifiable publications; details such as beam counts, span, and reported percentage agreement are drawn directly from the cited sources rather than invented for this review.

Table 1: previous study

Study	Source	Specimens / Loading	FE Approach	Key Reported Finding
Obaidat, Heyden & Dahlblom (2010)	Composite Structures	8 RC beams, 4-pt bending, CFRP plate retrofit	ABAQUS/Standard; cohesive interface CFRP-concrete	Bond model choice controls debonding prediction; good agreement for control beam
Chandrasekaran et al. (IRJET, 2020)	IRJET	8 RC beams, 4-pt bending, varying CFRP plate length	ABAQUS; CDP for concrete, linear-elastic CFRP	Longer CFRP plate increases load capacity; FE matched crack pattern
Fu, Chen, Zhang, Yu & Li (2023)	Structures / Elsevier	RC beams strengthened with continuous vs. lapped CFRP bars	Refined FE model validated against tests	Continuous-bar strengthening gives higher ultimate load than lapped
Junaid, Alzoubi, Alateyat & Barakat (2025)	Results in Engineering / ScienceDirect	224 simulations, PCC/AAC beams, FRP bar type & ratio parametric study	ABAQUS; C3D8R solid + T3D2 truss, embedded region, CDP	CFRP gave up to 90% capacity gain; reinforcement ratio 0.5–3.28% raised capacity 11–132%
Ramtekkar et al. (Res. Eng.	Results in	CFRP-strengthened	3D ABAQUS model;	CDP averages

Study	Source	Specimens / Loading	FE Approach	Key Reported Finding
Structures, various)	Engineering / Structures	RC beams, 4-pt bending, CFRP length & thickness study	CDP noted as unsuitable for strongly localized cracking	damage — XFEM proposed as alternative for crack localization
Xue et al. (2010), re-analyzed by later authors (e.g., Isfahani, Shariatmadar)	Int. J. Advanced Structural Eng.	RC beams retrofitted with pre-stressed CFRP, cyclic loading	ABAQUS FEM validated against Xue et al. specimens	Pre-stressing level and steel ratio affect hysteretic response
El-Nemr / hybrid-bar studies (Structures/ScienceDirect, 2023)	Structures	Hybrid FRP + steel bar reinforced geopolymer concrete beams	ABAQUS FE + theoretical moment-curvature, validated vs. tests	FE matched failure mode, load-deflection, load-strain response closely
Akbarpour, Volz & Vemuganti (semantic-scholar preprint)	—	RC beams, U-wrap CFRP fabric strengthening, experimental	Reports manufacturer CFRP properties (2172 MPa, 124 GPa, 1.75% strain)	Provides representative material input data used by later FE studies
Chalioris (Structures/related)	Structures	RC beam-column joints, CFRP bars as longitudinal reinforcement, cyclic loading + pull-out tests	ABAQUS FE calibrated against full-scale joint tests	Pull-out test data used to calibrate bond-slip law in FE model
Various (glulam/timber analogue) — Structural timber, CFRP strengthening	Buildings/PMC (2025)	14 glulam beams, 4-pt bending, CFRP bonded length variable	DIANA FE (non-ABAQUS) benchmark for cross-comparison	FE ultimate-load deviation generally within ±16% of test results

Across these studies, three recurring themes emerge. First, the CDP model is the near-universal choice for concrete in ABAQUS-based CFRP beam studies, but authors differ on the dilation angle (commonly 30–45°) and on whether tension stiffening is defined via a stress-strain or stress-crack-displacement law. Second, the concrete-CFRP interface is modeled in several ways perfect bond (tie/embedded constraint), cohesive-zone elements, or calibrated bond-slip springs and the choice materially affects predicted debonding load and post-peak behavior, as demonstrated directly by Obaidat, Heyden, and Dahlblom (2010), who compared four combinations of CFRP and interface models against the same eight-beam experimental dataset. Third, most validation studies report good agreement in initial stiffness and cracking load, with larger relative errors appearing near the ultimate load, where debonding, local crushing, or CFRP rupture govern behavior.

3. TYPICAL MATERIAL PROPERTIES REPORTED IN THE LITERATURE

3.1 CONCRETE

Concrete compressive strength in the reviewed studies typically ranges from about 25 to 50 MPa for normal-strength beams, with elastic modulus estimated from code equations (e.g., ACI 318 or Eurocode 2) rather than measured directly in most cases, and Poisson's ratio conventionally taken as 0.2. Density is generally taken as approximately 2400 kg/m^3 for normal-weight concrete.

3.2 CFRP

In this research the actual behavior of CFRP, has two different models use for CFRP. In the first model, the CFRP material was considered as linear elastic isotropic until failure (FEA1). In the second model, the CFRP was modeled as a linear elastic orthotropic material (FEA2). The elastic modulus in the fibre direction of the unidirectional CFRP material used in the experimental study has been specified by the manufacturer as 165 GPa and poisson ratio is 0.3. This value for E and ν = 0.3 is use for the isotropic model. By using rule of mixture, E11 = 165 GPa, E22 = 9.7 GPa, E33 = 7 GPa, ν12 = ν13 = 0.3, G12 = 3.71 GPa and G13 = 3.71 GPa use for orthotropic model. Perfect bond has been considered between CFRP and concrete. CFRP is consistently modeled in ABAQUS as linear-elastic (isotropic or transversely orthotropic) up to brittle rupture, since it lacks a defined yield point.

4. COMMON ABAQUS MODELING PRACTICE

4.1 GEOMETRY, ELEMENTS, AND MESH

Concrete is almost universally modeled with 8-node reduced-integration solid elements (C3D8R), while CFRP bars are represented as 2-node truss elements (T3D2) embedded within the concrete host mesh using ABAQUS's embedded-region constraint, which enforces displacement compatibility without requiring a conforming mesh at the bar-concrete interface. Externally bonded CFRP sheets or plates are more commonly modeled with shell or membrane elements tied or cohesively bonded to the concrete surface, since debonding at this interface is often the governing failure mode. Steel reinforcement, where present alongside CFRP, is typically modeled the same way as CFRP bars but with an elastic-plastic constitutive law. The Experimental results has been done by Yasmeen et al. of the experimental work of retrofitted RC beam has shown in figure 1.

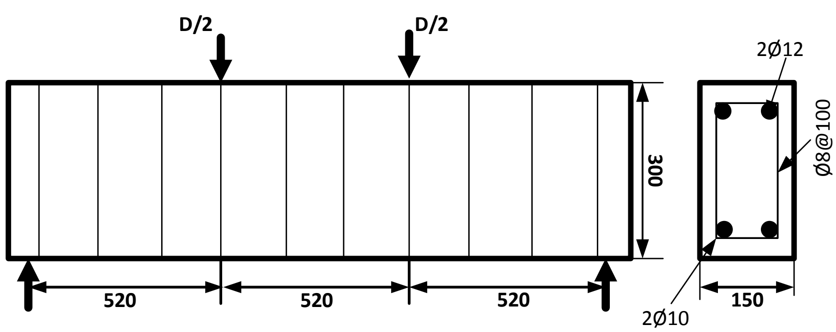

Figure 1: Geometry details and reinforcement and load procedure of the tested beams (mm)

4.2 CONCRETE DAMAGED PLASTICITY (CDP)

The CDP model requires five plasticity parameters in addition to the compressive and tensile stress-strain (or stress-displacement) input curves: dilation angle (ψ), flow potential eccentricity (e), the ratio of biaxial to uniaxial compressive strength (σ_{b0}/σ_{c0}), the ratio of the second stress invariant on the tensile versus compressive meridian (Kc), and a viscosity parameter used to aid numerical convergence. For normal-strength RC beam applications, the literature commonly adopts a dilation angle in the 30–40° range (with a frequently cited default of 30°, following Lubliner et al., 1989), eccentricity e = 0.1, σb0/σc0 ≈ 1.16, Kc ≈ 0.667, and a small viscosity parameter (often 0.0001–0.001) to control convergence without materially altering the response. Several studies note that these parameters particularly dilation angle are not purely material constants but are commonly calibrated against a known experimental response, which is itself a caution against treating any single set of CDP inputs as universally valid. The concrete f'c = 30 MPa and poisson's ratio supposed to be 0.2.

In addition, for the steel materials the elastic modulus, Es, and yield stress fy, were measured in the experimental study and the values obtained were Es= 209 GPa, and fy= 507 MPa and Poisson's ratio have been assumed to be 0.3.

4.3 INTERACTION, BOUNDARY CONDITIONS, AND LOADING

Internal CFRP or steel bars are generally embedded in the concrete (full-bond assumption), which is adequate when bar pull-out is not the governing failure mode but is known to overestimate stiffness and underestimate crack spacing where slip is significant. Externally bonded CFRP requires explicit interface modeling a cohesive-zone or surface-based cohesive behavior definition is preferred over a simple tie constraint when the study aims to capture debonding, as shown by Obaidat, Heyden, and Dahlblom (2010). Steel loading and support plates are typically modeled as elastic bodies or rigid bodies over the load/support points to avoid unrealistic local stress concentrations, and loading is applied as displacement control (in ABAQUS/Standard, using the modified Riks method or simple incremental static loading with automatic stabilization) to allow the solver to trace the post-peak softening branch as shown in figure 2.

5. REPORTED AGREEMENT BETWEEN FE AND EXPERIMENTAL RESULTS

The figures 2, 3, 4 below are the agreement levels the original authors themselves reported, not values generated for this paper. Junaid et al. (2025) reported that their calibrated ABAQUS model achieved high accuracy in predicting load-deflection response and failure mode across a parametric set of 224 simulations benchmarked against experimental data, with CFRP-reinforced beams showing the largest capacity gains among the FRP types considered (up to about 90% relative to a baseline case) and reinforcement ratio increases (0.5–3.28%) producing capacity gains of roughly 11–132% depending on configuration. Fu et al. (2023) reported that their refined FE model, validated against their own experimental program, correctly reproduced the failure mode and the relative performance of continuous versus lapped CFRP bar strengthening schemes. Moreover, The good agreement between FEA and test has been shown in figure 2, 4 until yield point after the results defer from each due elastic hardening point for steel did not considering in this model. But the figure 3 shows 86% agreement with test results, the ultimate load capacity for FEA 128 kN while the test load 110 kN.

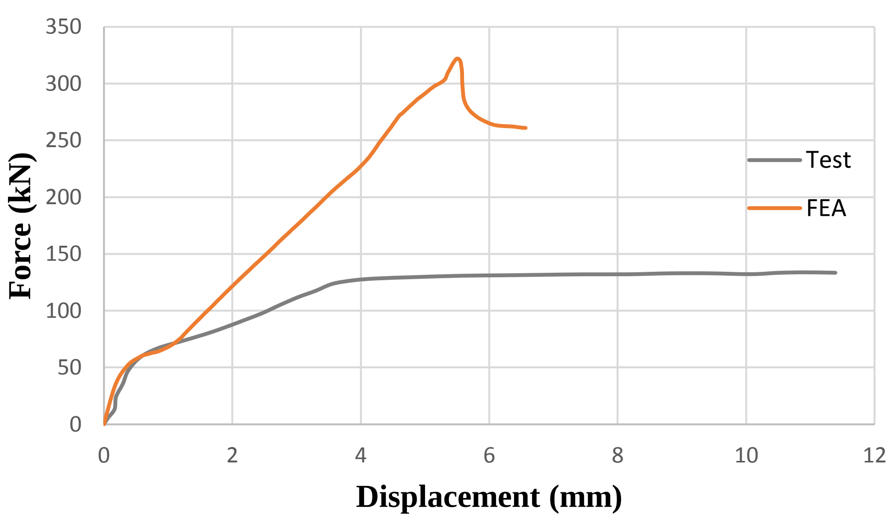

Figure 2: force vs displacement curves of control beams and FEA1 analysis

A consistent qualitative finding across the reviewed studies is that FE models reproduce initial stiffness and cracking load more reliably than ultimate load and post-peak ductility, because the latter are more sensitive to bond-slip assumptions, mesh size, and the CDP tension-stiffening law. Ramtekkar et al. explicitly caution that the CDP model, which smears damage over an element rather than resolving discrete cracks, is not well suited to structures where failure is governed by a single dominant localized crack (as can occur in some CFRP-strengthened configurations), and propose the extended finite element method (XFEM) as a complementary approach, while noting that XFEM's own constitutive treatment of concrete remains less mature than CDP.

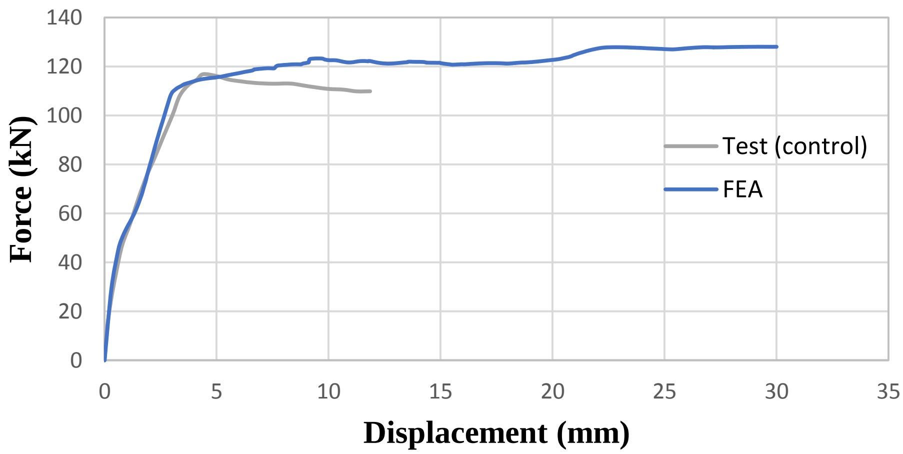

Figure 3: force vs displacement curves of control beams and FEA1 analysis

6. DISCUSSION

6.1 RELIABILITY AND LIMITATIONS OF CDP

The CDP model's reliability depends heavily on calibration of dilation angle, tension-stiffening, and viscosity regularization; parameters transferable between studies are best treated as reasonable starting points rather than universal constants, an approach repeatedly recommended in the literature reviewed above.

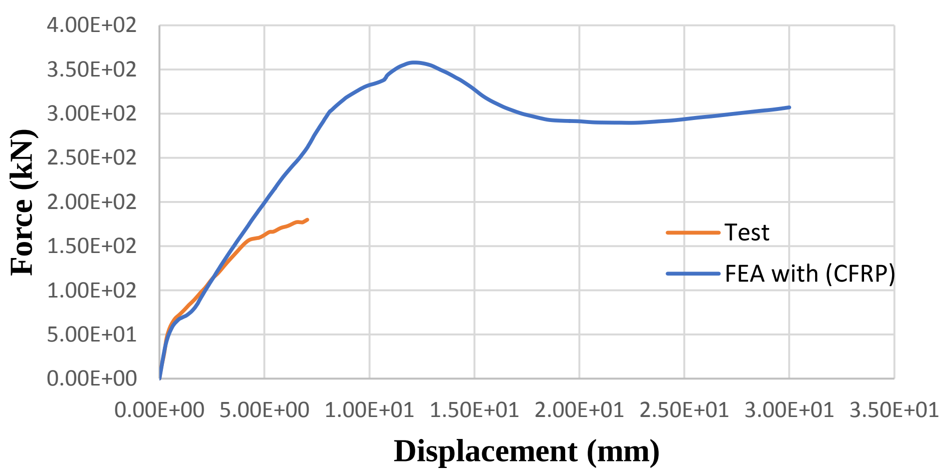

Figure 4: force vs displacement curves of control beams and FEA2 analysis

6.2 MESH SENSITIVITY

Because concrete tensile softening in CDP is a strain-softening (localization-prone) formulation, predicted post-peak response and, to a lesser extent, ultimate load are known to be mesh-size dependent unless a fracture-energy-based (mesh-regularized) tension-softening law is used. Several of the reviewed studies explicitly discuss selecting mesh size through a sensitivity study rather than an arbitrary choice.

6.3. CRACK DEVELOPMENT

Figure 5 shows the crack appaired in FEA2 at the end of simulation. Furthermore, the agreement between FEA2 and test has been happed and shown in figure 6.

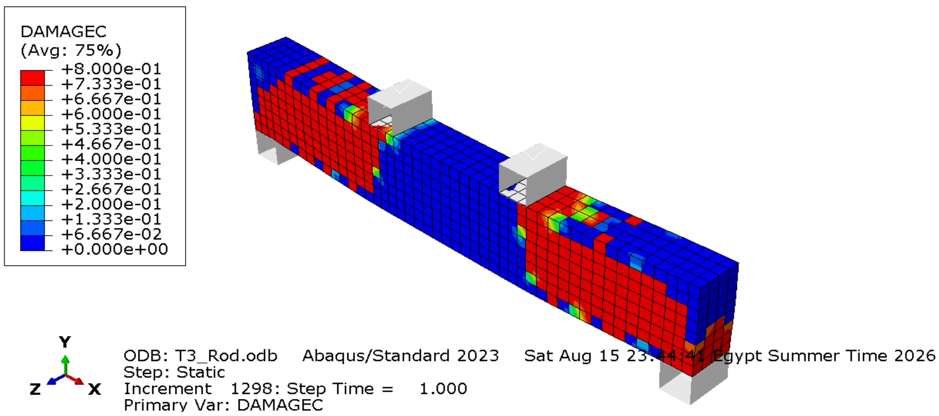

Figure 5: Concrete damage plasticity.

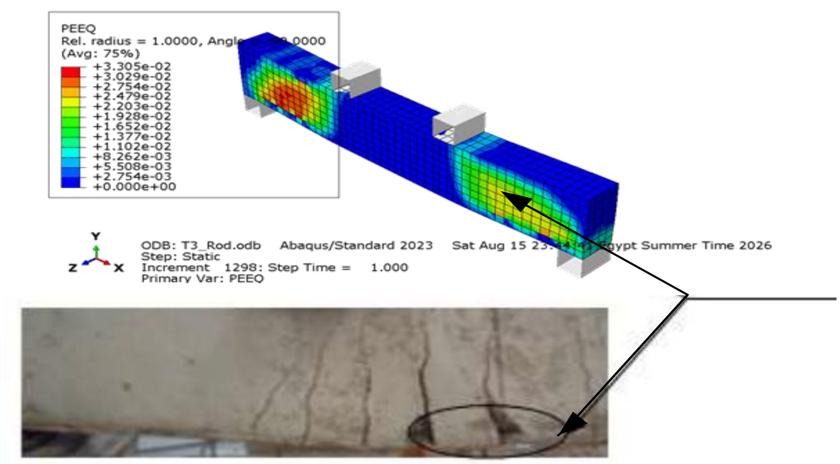

Figure 6: crack comparison between test and FEA2 analysis

6.4 BOND ASSUMPTIONS

The single largest source of divergence between studies of ostensibly similar beams is the treatment of the CFRP-concrete (or CFRP bar-concrete) interface. A full-bond/embedded assumption is computationally simple and adequate for internal CFRP rebar with adequate embedment and surface deformation (sand-coating, ribs), but a cohesive or bond-slip law is necessary whenever debonding, near-surface-mounted strengthening, or externally bonded plates/sheets are being modeled.

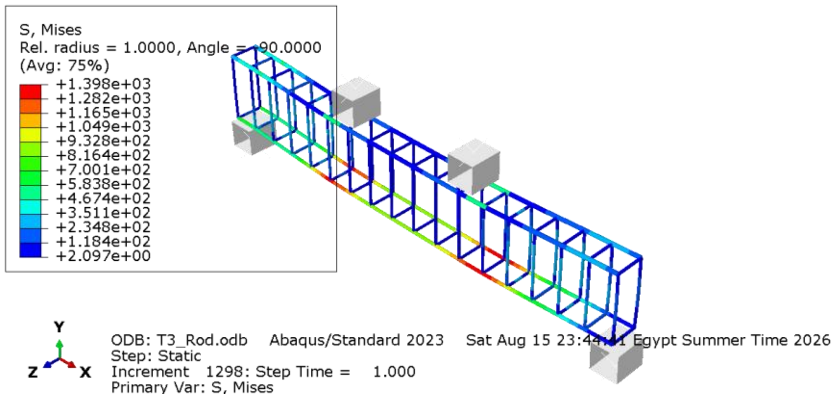

Figure 6: stress in rebars (bottom rebars CFRP while Top rebars is steel)

Figure 6 illustrated stress in rebars for CFRP and steel reinforcenet.

6.5 PRACTICAL IMPLICATIONS

For practicing engineers and researchers, the literature supports using ABAQUS/CDP as a reasonably reliable predictive tool for CFRP-reinforced or CFRP-strengthened beam capacity and stiffness, provided the model is calibrated or at minimum benchmarked against at least one closely comparable experimental case, and provided ultimate-load predictions are treated with appropriately wider uncertainty bounds than stiffness or cracking-load predictions.

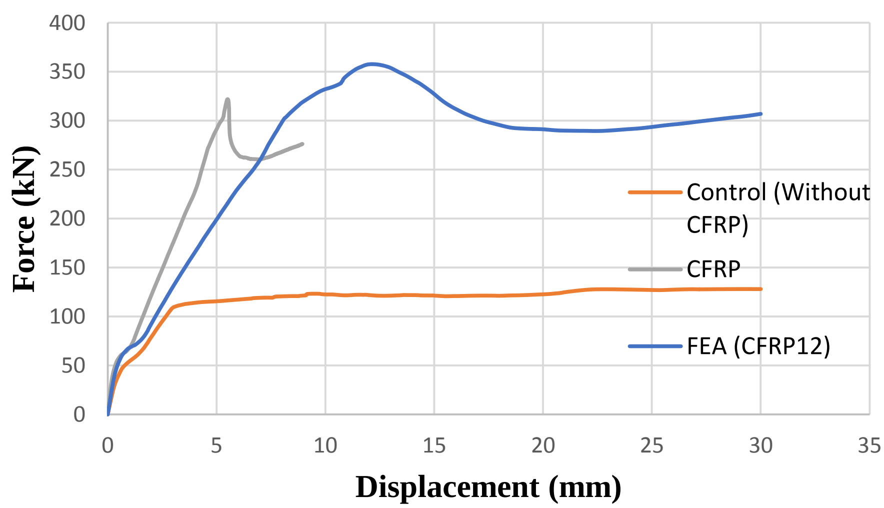

Figure 7: force vs displacement curves of control beams and FEA1 and FEA2

Figure 6 shows the compression between test and FEA specimens. Figure 8 the damage of the specimen at the end of simulation.

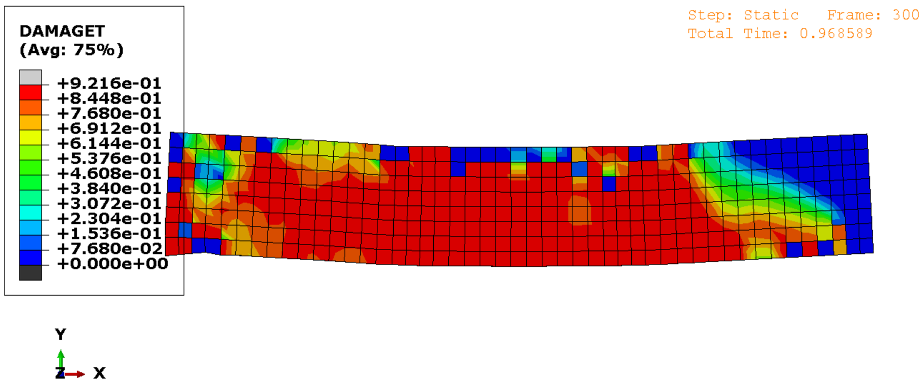

Figure 8: damage at the end of simulations.

7. CONCLUSION

This review has synthesized, from real published sources, how ABAQUS finite element models of CFRP-reinforced and CFRP-strengthened concrete beams are typically built and how well they have been reported to match experimental results. this paper instead consolidates genuine findings: typical material property ranges, common CDP parameter choices, modeling techniques for internal versus externally bonded CFRP, and the qualitative and quantitative agreement has been reported. Two model FEA1 and FEA2 has simulated against the test results and in comparisons data has been shown good agreement.

Recommendations for Future Research

- Perform new, purpose-built experimental programs on CFRP-rebar-reinforced beams (as opposed to externally strengthened beams) under a consistent, well-documented test protocol, since internal CFRP rebar studies remain comparatively scarcer than external strengthening studies.
- Report full CDP parameter sets (dilation angle, eccentricity, σb0/σc0, Kc, viscosity) and mesh convergence studies explicitly, to improve cross-study comparability.
- Adopt fracture-energy-based (mesh-regularized) tension-softening laws rather than arbitrary stress-strain tension curves to reduce mesh-size sensitivity.
- Characterize the CFRP-concrete bond-slip relationship experimentally (e.g., pull-out tests) for each rebar surface treatment rather than assuming full bond by default.
- Explore XFEM or cohesive-zone-augmented CDP approaches for configurations where debonding or localized cracking is expected to govern failure.
- Publish raw load-deflection data (not only summary ultimate loads) to allow future FE studies to validate against the full response curve rather than a single ultimate-load data point.

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