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Finite Element Modelling and Numerical Investigation of Flexural Behaviour of Hybrid-Reinforced Concrete Beams Using ABAQU

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Abstract
In structural engineering, reinforced concrete beams are common, although typical steel reinforcement is prone to corrosion and durability issues. Hybrid reinforcing systems using steel and GFRP bars may improve structural performance and service life. Recent innovations in hybrid reinforcement technology have enhanced strength, crack resistance, and durability. However, few numerical studies of hybrid-reinforced concrete beam flexural behaviour exist. This work employs finite element modelling to investigate the flexural behaviour, load-carrying capability, crack propagation, and structural performance of hybrid-reinforced concrete beams. Modelling steel, GFRP, and hybrid reinforced concrete beams with ABAQUS finite element software. Numerical results from nonlinear studies under flexural loading were compared to theoretical predictions. Compared to conventional reinforcing systems, hybrid-reinforced beams had higher flexural strength, fracture control, stiffness retention, and ductility. The finite element findings matched analytical predictions. Concrete beams with hybrid reinforcement are more efficient and durable, making them suitable for sustainable and high-performance infrastructure.

Keywords: *Hybrid Reinforcement, Reinforced Concrete Beams, Finite Element Analysis, ABAQUS, Structural Performance, Crack Propagation.*

Introduction
Advanced reinforcement technologies that overcome steel reinforcement's limitations have been developed to meet the growing need for durable and high-performance reinforced concrete structures. Hybrid reinforcement, which blends steel bars with FRP materials, may improve structural strength, durability, corrosion resistance, and service life. Hybrid-reinforced concrete beam flexural behaviour under complicated stress situations has been studied extensively in recent years. Finite element modelling can forecast reinforced concrete members' nonlinear reaction and assess their structural performance before implementation [1]. Hybrid reinforcement systems improve load-carrying capacity and fracture control by balancing steel reinforcement's ductility with FRP materials' high tensile strength and corrosion resistance [2]. Numerical modelling has also been used to simulate hybrid concrete beam behaviour and validate experimental results, minimising the requirement for extensive laboratory testing [3]. Hybrid fibre-reinforced concrete has shown improved stress-strain, energy absorption, and structural robustness under loading [4]. The structural response, load capacity, and failure characteristics of hybrid-reinforced concrete beams under flexural loading are evaluated using ABAQUS finite element modelling and numerical research.

Literature review
The following section elaborates on the past literature related to this study in detail.

Table 1: Related works

Authors and Year	Methodology	Key Findings
[5]	Utilized numerical sensing techniques to investigate plastic hinge development in concrete beams reinforced with hybrid FRP and steel bars.	The study demonstrated improved structural monitoring and enhanced flexural performance in reinforced concrete beams.
[6]	Performed numerical investigation of steel–FRP reinforced concrete moment-resisting frames subjected to lateral loads using finite element modelling.	The hybrid system improved seismic performance compared with conventional reinforcement.
[7]	Investigated the flexural performance of hybrid concrete T-beams through nonlinear numerical modelling and structural analysis.	The numerical model successfully predicted the failure mechanisms and deformation behavior of T-beams.
[8]	Conducted finite element modelling of hybrid concrete tee beams reinforced with GFRP bars and evaluated their flexural behavior under loading.	Hybrid GFRP reinforcement improved load-carrying capacity, reduced crack propagation, and increased overall beam stiffness. Numerical predictions showed good agreement with experimental observations.
[9]	Performed finite element analysis on ultra-high-strength concrete beams reinforced with BFRP and hybrid BFRP–steel reinforcement systems.	Hybrid BFRP–steel reinforcement achieved superior flexural strength, improved ductility, and enhanced energy absorption compared with beams reinforced solely with BFRP bars.

Research Gap

Several studies have examined hybrid-reinforced concrete structures, but improved finite element modelling approaches are needed to fully evaluate flexural performance. Previous research focused on hybrid fiber-reinforced concrete, hybrid GFRP-steel reinforcing systems, and T-beams and moment-resisting frames. These studies improved strength, ductility, and crack resistance, but little was known about hybrid-reinforced concrete beams' nonlinear flexural behavior, stress distribution, crack propagation, and failure mechanisms under different reinforcement configurations. Most research focused on experimental testing or analytical modeling, with few presenting validated ABAQUS-based finite element models that accurately simulated concrete, steel reinforcement, and GFRP reinforcement. Comparative studies of conventional steel-reinforced, GFRP, and hybrid beams are lacking. Thus, a detailed computational study is needed to assess hybrid-reinforced concrete beams' structural efficiency, load-carrying capacity, stiffness, and failure behaviour under flexural stress.

Methodology

The study examined hybrid-reinforced concrete beam flexural behavior using ABAQUS software and computational finite element modelling. Based on geometric dimensions and material parameters from prior experimental research, reinforced concrete beam specimens with conventional steel, GFRP, and hybrid reinforcing systems were modeled. Concrete, longitudinal reinforcing bars, and stirrups were modeled, followed by constitutive material models. The beam components were built, and interaction features were determined to approximate concrete-reinforcement bonding. Four-point bending test boundary conditions and loading arrangements were then applied. Load–deflection, stress distribution, fracture onset, and failure processes were assessed using nonlinear static analysis. The numerical results from ABAQUS were compared to analytical predictions and experimental data from the literature to validate the model and evaluate the effect of hybrid reinforcement on flexural performance.

Results and Discussion

Finite element analysis of reinforced concrete beams subjected to flexural loading using ABAQUS software yields numerical results. The numerical investigation examined the structural performance, flexural behaviour, load-carrying capacity, deformation characteristics, and crack propagation patterns of beams reinforced with conventional steel bars, GFRP bars, and hybrid reinforcement systems. The interaction between concrete and reinforcing materials under loading circumstances was investigated using finite element modelling. Material attributes and constitutive models were assigned to beam components: concrete, longitudinal reinforcement, and stirrups. The beam models used the experimental setup's boundary conditions and loads. Post-processing yielded stress distributions, displacement patterns, strain responses, and failure mechanisms.

In addition to finite element simulations, analytical predictions based on previous literature models were compared. This comparison confirms the numerical model and assesses the finite element approach's reinforced concrete beam flexural response forecast accuracy and dependability. This section covers load–deflection, ultimate load capacity, stiffness, stress distribution, and fracture formation. Different reinforcement configurations' impacts on structural performance are examined. Numerical observations and analytical expectations show similarities, differences, and structural response reasons. The study shows that hybrid reinforcing systems can increase reinforced concrete beam flexural performance from conventional approaches.

Figure 1 shows how to transform 'Module' to 'Part' to build a specific model component.

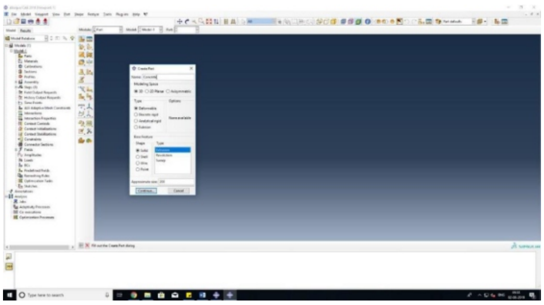

Figure 1: Part module in ABAQUS

The ABAQUS finite element analysis revealed the flexural and structural response of hybrid-reinforced concrete beams under monotonic loading. The simulated findings showed that the finite element models accurately captured reinforced concrete beam load transfer mechanisms, stress distribution patterns, deformation features, and crack propagation behaviour. The load–deflection responses from the simulations showed that hybrid reinforcement systems improved structural performance compared to standard steel or GFRP bars. The initial loading of all beam specimens showed almost linear elastic behaviour, indicating successful concrete-reinforcement composite action. As the load grew, microcracks formed in the concrete section's tension zone, reducing stiffness. However, hybrid-reinforced beams had delayed crack onset and lower crack widths, indicating better crack management. The improved behaviour is due to the steel reinforcement's ductility and yielding capacity, and GFRP reinforcement's high tensile strength and corrosion resistance. ABAQUS stress contour plots showed hybrid beams had a more uniform stress distribution, decreasing stress concentration effects that cause premature failure. The hybrid reinforcing technique also boosted the beam's energy absorption capability, allowing it to withstand higher loads before destruction. The finite element model predicted greater ultimate load capacities for hybrid-reinforced specimens, indicating the favourable interaction between reinforcing materials. These findings suggest that hybrid reinforcement can overcome various traditional reinforcing system constraints while retaining structural safety and serviceability. The illustration using ABAQUS is given below.

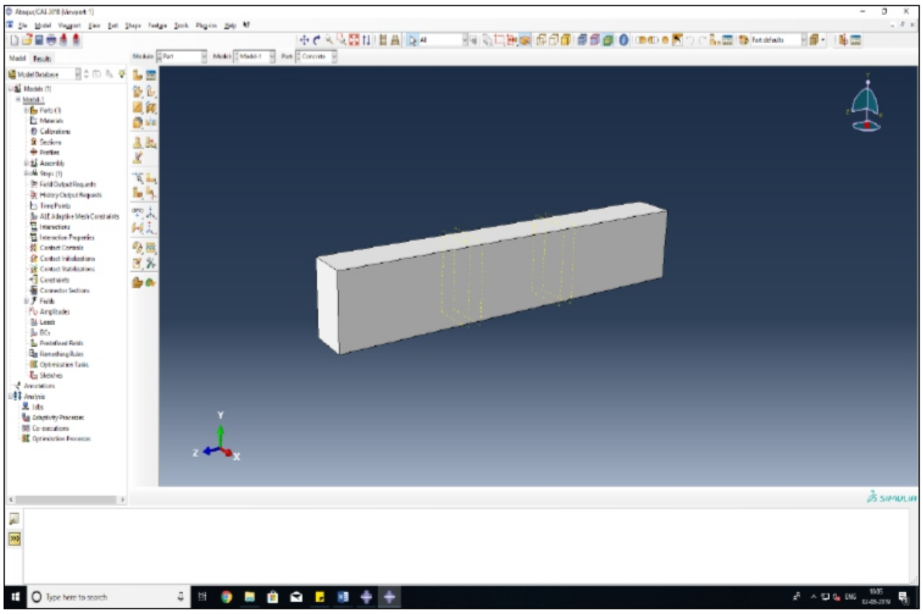

Figure 2: Illustration using ABAQUS

Table 2 compares experimental ultimate loads to theoretical flexural and shear capacity to corroborate the numerical findings.

Table 2: Comparison of predicted and experimental ultimate flexural strength

Sl. No.	Beam ID	Exp. ultimate flexural load (Pflexp) (kN)	Exp. ultimate shear (Psexp) (kN)	Predicted ultimate load (Flexure) (Pftheo) (kN)	Predicted ultimate load (Shear) (Pstheo) (kN)	Ratio (Pftheo/Pfexp)
1	BS150	97.3	48.7	61.8	75.5	0.64
2	BS300	96.1	48.1	61.8	45.6	0.64
3	BG150	74.6	37.3	85.5	68.4	1.15
4	BG300	56.8	28.4	85.5	38.1	1.51
5	400HBG150	127.5	63.8	108.6	71.2	0.85
6	800HBG150	94.1	47.1	108.6	71.2	1.15
7	1400HBG150	70.6	35.3	108.6	71.2	1.54
8	1400HBG300	60.3	30.2	108.6	40.6	1.80
9	400HBC150	98.3	49.2	100.9	71.2	1.03
10	800HBC150	105.0	52.5	100.9	71.2	0.96
11	1400HBC150	100.1	50.1	100.9	71.2	1.01
12	1400HBC300	63.5	31.8	100.9	40.6	1.59

After processing, the hybrid reinforcing technique significantly influenced beam failure mode and flexural performance. ABAQUS models indicated that linear elastic FRP bars made GFRP beams brittle, while steel-reinforced beams crushed reinforcement and concrete. Hybrid beams showed controlled cracking, stiffness deterioration, and enhanced ductility before failure. The numerical fracture patterns demonstrated that hybrid beam crack propagation was more evenly distributed along the span, enhancing concrete section usage and minimising damage localisation. Hybrid beams demonstrated lower mid-span deflections under identical loading conditions, indicating improved flexural rigidity and stiffness retention. Numerical results matched analytical expectations from previous studies, confirming the finite element model. Analytical and numerical results differed slightly due to modelling assumptions, material idealisations, and analytical formulation simplifications. The patterns remained consistent, indicating that ABAQUS can effectively simulate the complex interaction between concrete, steel, and GFRP reinforcement.

Hybrid reinforcement systems offer promise for structural applications that involve durability, crack resistance, load-carrying capability, and long-term performance. Hybrid reinforcement in reinforced concrete beams can construct durable, strong, and efficient structures.

Conclusion

It used ABAQUS finite element modelling to study hybrid-reinforced concrete beam flexural behaviour. Numerical study showed that hybrid steel-GFRP reinforcing systems outperform conventional reinforcement methods. The hybrid beams had better load-carrying capability, crack management, stiffness retention, and flexural ductility. The numerical model's dependability and accuracy were confirmed by finite element results that matched theoretical and experimental results. The hybrid reinforcement system matched steel and GFRP benefits, improving durability and structural efficiency. The study concludes that hybrid reinforcement is a promising and sustainable method for designing high-performance reinforced concrete structures.

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