



## Optimizing Reinforcement Strategies for Concrete Deep Beams under Impact Loads

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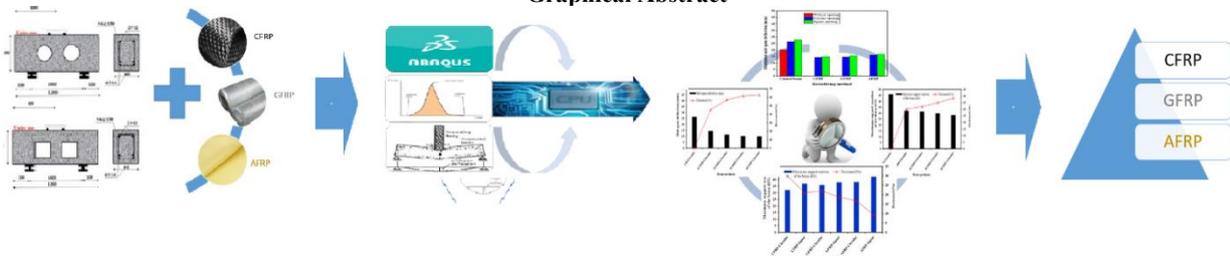
Fiber-Reinforced Polymer laminates  
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### A B S T R A C T

This research investigates the dynamic performance of reinforced concrete deep (RCD) beams subjected to impact loads, focusing on the influence of reinforcement strategies and opening configurations on their structural behavior. Finite element (FE) analysis techniques are utilized to model various scenarios, incorporating different types and numbers of fiber-reinforced polymer (FRP) laminates and geometric configurations of openings. The findings demonstrate that reinforcement with FRP laminates significantly reduces mid-span deflection and maximum support reaction. Among the laminates, carbon FRP (CFRP) shows superior performance compared to aramid FRP (AFRP) and glass FRP (GFRP). Additionally, beams with circular openings exhibit better performance in minimizing mid-span deflection and support reaction compared to those with rectangular openings. However, increasing the number of CFRP layers, while enhancing structural performance, presents economic challenges due to diminishing returns in load-bearing capacity improvement. These results highlight the importance of carefully balancing reinforcement strategies, opening shapes, and cost-effectiveness to optimize the stability and performance of RCD beams under impact loads.

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### Graphical Abstract



## 1. INTRODUCTION

The rapid development observed in several developing countries has spurred the widespread construction of tall towers and skyscrapers. As a consequence of the substantial loads imposed by these towering structures, reinforced concrete deep (RCD) beams are frequently employed in lower floors as transfer beams, tasked with distributing loads from the entire building to the foundations (1). Within reinforced concrete structures,

deep beams serve a multitude of purposes, functioning as load-bearing girders, pile caps or integral components of tall building walls. They constitute vital elements in civil engineering, finding applications in tall towers, folded slabs, shear walls, floor diaphragms and offshore structures. According to the ACI 318 code (2), a reinforced concrete beam qualifies as a deep beam if the ratio of shear span to total depth is four or less, and if the point load is positioned at a distance equal to twice the beam height from the support. In comparison to standard

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beams, RCD beams display a more intricate behavior, particularly under conditions of dominant shear failure that predispose them to shear rupture. Consequently, the resistance of these beams is typically governed by shear, with their primary weakness manifested in low shear capacity and susceptibility to shear failure under seismic loads. Various methodologies, such as reinforced concrete jackets, steel plates as external wraps, localized retrofitting, and external prestressing are employed to strengthen and rehabilitate these beams (3-6). The application of Fiber Reinforced Polymer (FRP) for the refurbishment and enhancement of structures has experienced a significant rise in recent years (7-9). Notably, recent research has been concentrated on the utilization of carbon FRP (CFRP) layers to augment the structural integrity of RCD beams (4, 10-12). Islam et al. (13) observed a 40% increase in shear capacity attributable to externally bonded FRP systems, while Rahim et al. (11) reported a 10-40% augmentation in load-bearing capability of beams with openings through the deployment of CFRP laminates. Furthermore, investigations into alternative types of FRP laminates, such as glass FRP (GFRP) and hemp fibers, have been conducted for the reinforcement of RCD beams (14-16). Recent studies confirm that CFRP retrofitting enhances the seismic performance of historical buildings. For example, researches on a monumental structure in Cappadocia (17) and in Nigde (18), Turkey, showed that CFRP surface coatings significantly reduced lateral drift under seismic loads. These findings highlight FRP's effectiveness in strengthening reinforced concrete structures against seismic and impact loads.

The necessity of accommodating mechanical and electrical installations within concrete structures, coupled with architectural considerations, has necessitated the creation of openings in these structures. Deep beams, being primary members affected by such openings due to their height, provide ample space for these openings; thus, requiring a thorough assessment and reinforcement to mitigate the reduction in load-bearing capacity (19, 20). Openings are among the factors diminishing load-bearing capacity, potentially causing irreversible damages if not considered in structural designs (21, 22). Proposed solutions include the use of FRP composite laminates (23, 24); although limited research exists on this type of reinforcement for deep beams with openings. Moreover, design codes have overlooked the effects of composite materials on reinforcing such elements, highlighting the growing need for further examination (25). El-Maaddawy and Sherif (23) demonstrated a 73% increase in shear capacity of beams by loading two points on deep beams reinforced with CFRP laminates and featuring square openings. Chin and Doh (26) stated that circular holes can reduce the beam's load-bearing capacity, while square holes can create a much greater reduction in it.

Due to the varying nature of concrete's response to high strain rate loading, traditional static loading assessments are insufficient to predict its behavior under high strain rates. Since this domain is relatively new with numerous benefits and its conduct is not entirely understood, comprehensive comprehension is essential for practical implementation in the construction industry. Consequently, further investigation in this realm is imperative to advance research in this field. Some researchers have studied the effect of dynamic and impact loads on reinforced concrete shallow beams from various perspectives (27-31). Because of the beam's substantial acceleration from impact force, its inertia force becomes most prominent, particularly within the initial milliseconds when the beam counteracts the impact solely through inertia, preceding the load reaching the support. The force from impact speeds up the beam and applies its inertia force (32). Neglecting the inertial force results in inaccuracies when determining the breakage of reinforced concrete beams if designers equate the imposed impact load with the bending load supported by the beam (33). Most of the impact energy is resisted by beam inertia, with only a small amount withstanding by the support, primarily due to the fast stress wave (34).

## 2. RESEARCH SIGNIFICANCE

Despite numerous research efforts on the reinforcement of RCD beams using various types of FRP, a review of the current literature did not uncover any comparative studies on their advantages in strengthening RCD beams. Moreover, even with notable advancements in the study of RCD beams over the past three decades, understanding of the dynamic shear resistance and performance of RCD beams under different loading rates remains restricted (35, 36). Therefore there is an urgent need for research in the comparison of various methods of reinforcing RCD beams with openings under high strain rate loads. This article investigates these two crucial concepts. An analytical comparison of FRP coatings, including carbon, glass, and aramid FRP (CFRP, GFRP, AFRP), is conducted for strengthening RCD beams with rectangular and circular openings under high strain rate loading. Importantly, this study differs from others in that it also investigates the influence of the number of FRP layers (one to four layers).

Concurrently with advancements in design and production technology, appropriate scientific methods must be employed to reduce costs, time, and address challenges. Relying solely on experiments for the design and production of ideal products is insufficient. The use of numerical methods in research problem analysis and production is a powerful tool for feasibility and forecasting conditions, integral to almost every scientific

field. A nonlinear finite element (FE) model based on experimental results is prepared using ABAQUS 6.11 commercial software (37). Finally, a comprehensive study is undertaken to gather as much information as possible on the subject.

**2.1. Objectives** Drawing from the aforementioned points, the aims of this study encompass the following:

- Numerical investigation the mid-span deflection (MSD) and the maximum support response of RCD beams featuring rectangular and circular openings when subjected to impact loads.
- Numerical evaluating the efficiency of FRP wrapping in repair of RCD beams with rectangular and circular openings regarding MSD and the maximum support response when subjected to impact loads.
- Exploring how different types of FRP (CFRP, GFRP, AFRP) affect the behaviour of RCD beams with circular and rectangular openings reinforced by a singular FRP laminate layer when subjected to impact loads.
- Investigating the influence of varying the number of FRP layers on the behaviour of RCD beams with circular openings, reinforced by a single layer of CFRP laminate, and employing two, three and four layers of CFRP under impact loads.

### 3. VARIABLES AND GEOMETRIES

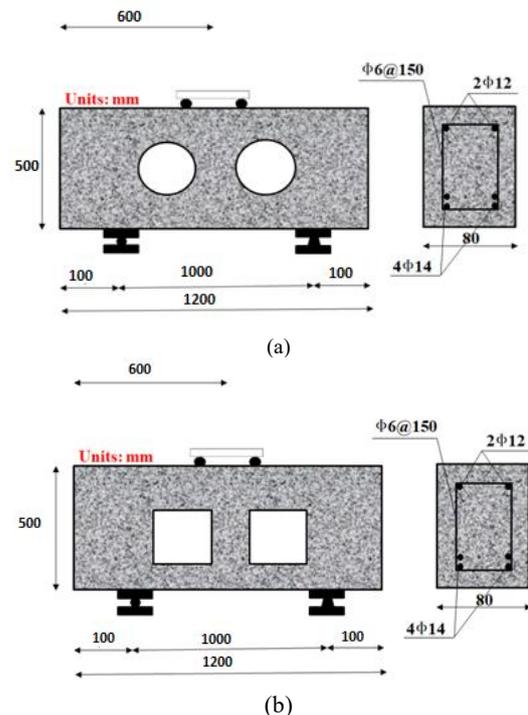
The present FE models were initially formulated with the objective of facilitating the expansion of numerical analyses and conducting a parametric investigation in subsequent phases. The incorporated variables encompassed the types of FRP laminates, geometric shape of openings, number of FRP layers. These parameters are delineated in Table 1, illustrating the models under scrutiny.

The beam measurements stood at 1200 mm in length, 80 mm in breadth, and 500 mm in height. Based on these dimensions, the ratios for effective length and shear span to total depth were calculated as 1000 mm and 2.5, respectively, indicating a substantial depth for the beams.

The dimensions of the openings were selected to maintain equal areas for both circular and rectangular openings. The circular openings had a diameter of 339 mm, while the rectangular openings measured 274 x 329 mm. Utilizing the designated criteria, a collective sum of 12 FE simulations of RCD beams underwent impact loading. These RCD beams, earmarked for strengthening with FRP laminates, adhered to ACI standards in their design and were exposed to four-point loading scenarios. A comprehensive summary outlining the mechanical and dimensional characteristics of the beams is provided in Figure 1.

**TABLE 1.** Introduction of FE models of RCD beams investigated

Beam name	Beam No.	FRP type	Number of layers	Openings shape	Openings position
CB	1	Without FRP	0	Without openings	-
CB-Circ	2	Without FRP	0	circular	middle
CB-Rec	3	Without FRP	0	rectangular	middle
1CFRP-Circ	4	Carbon	1	circular	middle
1CFRP-Rec	5	Carbon	1	rectangular	middle
1GFRP-Circ	6	Glass	1	circular	middle
1GFRP-Rec	7	Glass	1	rectangular	middle
1AFRP-Circ	8	Aramid	1	circular	middle
1AFRP-Rec	9	Aramid	1	rectangular	middle
2CFRP-Circ	10	Carbon	2	circular	middle
3CFRP-Circ	11	Carbon	3	circular	middle
4CFRP-Circ	12	Carbon	4	circular	middle



**Figure 1.** Physical and spatial attributes of the beams: (a) Beams with circular openings, (b) Beams with rectangular openings

### 4. NUMERICAL MODELLING

**4.1. Materials** With the advances in computer processing and analysis of structural components, the FE analysis method has become an effective tool for

analyzing the nonlinear and dynamic behavior of reinforced concrete under dynamic loads for the accurate modeling of the behavior of components such as steel reinforcement and concrete matrix and layer has been composited (38). The components examined in this research encompassed beams and FRP materials. Each element within ABAQUS possesses a distinct designation, such as T2D2, S4R, C3D8I, or C3D8R. These designations delineate the five attributes of an element. To replicate solid materials like concrete and adhesive, three-dimensional eight-node brick elements indicated by C3D8R were utilized (39). These C3D8R elements possess the capacity to emulate cracks in both tensile and compressive regions. Through the utilization of C3D8R elements, the progression of damage and element elimination using Scalar Stiffness Degradation (SDGE) can be employed to simulate crack propagation. The SDGE indicator functions as a gauge of stiffness reduction caused by cracks, fluctuating between 0 and a maximum degradation value. The assumed maximum degradation value is 1, given the current measure of SDGE hovering around 0.99, the procedure of gradual deterioration development and element elimination (referred to as SDGE) was calculated for every element in the assessments. Elements reaching peak degradation underwent no additional damage accumulation and were consequently extracted from the lattice realm. This Elimination of grid discretization aims to replicate crack propagation.

To model structural bars, one can use beam elements or truss elements. For this examination, truss components implementing three-dimensional lattice division (T3D2) were utilized to represent structural bars, encompassing steel bars. Every point of the axial compression-extension truss components was designated three translational freedoms.

Two primary divisions exist within constitutive models, namely Drucker-Prager and concrete damage plasticity, which can be employed to simulate the plastic behavior of concrete. The elastic characteristics of concrete substance were determined by Young's Modulus and Poisson's ratio (40), whereas the plastic reaction of concrete was replicated via concrete damage plasticity (concrete compression-tension damage), defined by factors such as compressive resilience, Poisson's ratio, expansion angle, biaxial to uniaxial compressive resilience proportion, shear resilience proportion between biaxial and triaxial compression, and fluidity. Bilal et al. (41) found that the concrete damage plasticity model surpasses the Drucker-Prager model in all scenarios, suggesting its superior precision in depicting the behavior of the composite column. The concrete damage plasticity model provides a benefit over Drucker-Prager by enabling the representation of stiffness reduction caused by crack initiation and

spreading through the employment of the SDGE parameter, hence it was selected for this analysis.

An elasto-plastic model with bilinear characteristics was proposed to depict the nonlinear performance of metal bars (39). In this particular model, metal bars displayed elastic tendencies until the imposed stress reached the yield threshold, following which there was a continuous occurrence of plastic distortion with a gradually escalating stress rate until eventual failure. Furthermore, a model of brittle fracture was utilized to depict the reaction of FRP composites to imposed loads.

Specifications for normal-weight concrete are presented in Table 2, while steel bars specifications are detailed in Table 3. FRP laminate specifications are provided in Table 4. The FE model was constructed using actual elastic-plastic material properties, stress-strain relationships, and nonlinearities. Material characteristics from Rahimi et al. (42) experimental study were incorporated for FE modeling of the beams.

**4. 2. Loading** Explicit dynamic analysis was employed to scrutinize the models under investigation. Building upon the research conducted by scholars such as Sierakowski and Chaturvedi (43) in static loading, it was assumed that the duration of load application exceeded the static response speed of the structure, ensuring the maintenance of internal balance throughout all stages of structural system loading. As the loading duration decreases, the influence of internal inertia

**TABLE 2.** Concrete specifications

Compressive strengths (MPa)	splitting tensile strengths (MPa)	Modulus of elasticity (MPa)	Poisson's ratio	ultimate strain of rupture
27.1	2.41	24467	0.15	0.0045

**TABLE 3.** Steel bars specifications

Rebar diameter (mm)	Ultimate stress (MPa)	Yield stress (MPa)
10	577	381
12	524	340

**TABLE 4.** Specifications of FRP laminates

FRP type	Ultimate strain (MPa)	Tensile strength (MPa)	Elasticity Modulus (GPa)	Thickness (mm)
AFRP	0.020	2800	110	0.210
GFRP	0.039	2300	90	0.157
CFRP	0.019	3950	235	0.084

becomes more pronounced, transforming the loading regime into dynamic loading. Consequently, the determination of structural response type hinges entirely upon the nature and expression of the system's loading.

Dynamic loading can be divided into two main types: vibration loading and impact loading. When loading is non-repetitive and applied for a limited duration, the structural response becomes transient or unstable. Following the transient phase, the response transitions into a permanent phase. Stress and deformation levels during the transient phase can be considerably high compared to those during the permanent phase, necessitating careful consideration by designers. Random vibrations occur in the structure when the momentary intensity of the load is uncertain for each moment, often described by probability distribution functions. Impact and impulse loads are examples of dynamic loads. If the loading duration is so brief that the materials within the system cannot sustain their continuity and integrity against loading, the structure is subjected to shock-like loading. In addition to parameters such as load duration and load grouping for classifying types of loading, the strain rate parameter can also be utilized (43). To refine the classification of existing loadings further, the relationship between strain rate and loading characteristic time for various types of loading is outlined in Table 5.

Kulkarni and Shah (44) scrutinized the dynamic response of reinforced concrete beams under high strain rates by hydraulic jack test. According to their investigation, a high strain rate of 38 cm/s (228 mm/min) was considered.

## 5. VALIDATION OF SIMULATION METHOD

The outcomes of experimental investigations were utilized to formulate and validate a nonlinear FE model, which was developed using ABAQUS commercial software (37). Initial numerical modeling was verified against the experimental findings of Rahimi et al. (42). For the validation of impact load simulations, data from

the experimental study conducted by Vu and Deeks (45) were employed.

This section provides a concise overview of the laboratory samples utilized for validating the simulations. GFRP and AFRP laminates were employed in retrofitting RCD beams with circular openings, serving as a comparison to CFRP laminates (42). Three beam samples, each incorporating three layers of various FRP laminates, were modeled according to the methodology outlined in the present study, and their response to static loading was assessed. The beams had dimensions of 500 mm in length, 150 mm in width, and 200 mm in height, with two circular openings positioned in the middle. Design criteria outlined by the ACI 318 code (2) were adhered to during the design of the deep beams. The second validation pertained to a beam evaluated in an experimental study conducted by Vu and Deeks (45).

Table 6 presents the specifications of the laboratory beam selected to validate the method of simulating high strain rate loading.

The transverse bars had a diameter of 3 mm and a yield stress of 250 MPa. The materials utilized in the study are outlined in Table 7. The load was applied to the specimens using a 160 kg impact-weight steel dropped from a free height.

Figure 2 illustrates the comparative load deflection diagrams of both the FE models and the laboratory samples. These graphs depict a reasonable correlation between the outcomes of experimental testing and numerical modeling. Therefore it can be said that the FE method used in the present study has a relatively good accuracy.

## 6. DISCUSSION AND EXAMINATION OF RESULTS

In this research, the influence of the type of RCD beams, opening shape and the effect of the type and number of FRP laminates on the MSD and the maximum reaction of beam supports have been investigated using ABAQUS 6.11 software (37). To achieve this goal, initially, a RCD

**TABLE 5.** Load duration and related strain rates (43)

The usual method of bleaching	Fixed load	Hydraulic or screw jack	Mechanical or pneumatic jack	Mechanical or explosive impact	Impact gas canisters or explosive pistols
Characteristic time (s)	$10^4$ to $10^6$	1 to $10^2$	$10^2$	$10^{-4}$	$10^{-8}$ to $10^{-6}$
Strain rate ( $s^{-1}$ )	$10^{-6}$ to $10^{-8}$	$10^{-2}$ to $10^{-4}$	1	$10^2$	$10^4$ to $10^6$
Properties of dynamic behavior	The force of inertia is negligible			Inertial forces are important	

**TABLE 6.** Specifications of selected laboratory beam (45)

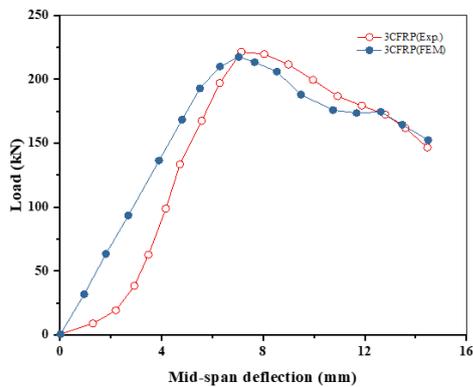
No.	Main Reinforcement	Drop Height (mm)	Type of Loading	Shear/ Bending Capacity ratio	Bending Capacity	Shear Capacity
A4-I	4-N12	1900	Impact	0.63	80 kN	50 kN

**TABLE 7.** Characteristics of materials used in the selected laboratory beam(45)

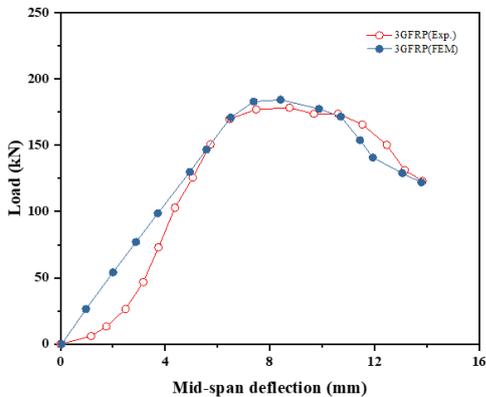
Properties	Ribbed wires	Steel Rebars	Concrete (at 28days)
Gravitational Mass density: m (kg/m <sup>3</sup> )	7,850	7,850	2,185
Tensile strength: ft (MPa)	850	600	-
Compressive Strength: fc (MPa)	-	-	34,0
Young's Modulus: E (MPa)	200,000	200,000	29,450

beam without opening was studied. Then, the MSD and the maximum reaction of supports of RCD beams with circular and rectangular openings were examined. Finally, the effect of FRP laminates in circular and rectangular ones, as well as the effect of the number of FRP layers in circular beams, were studied and analyzed.

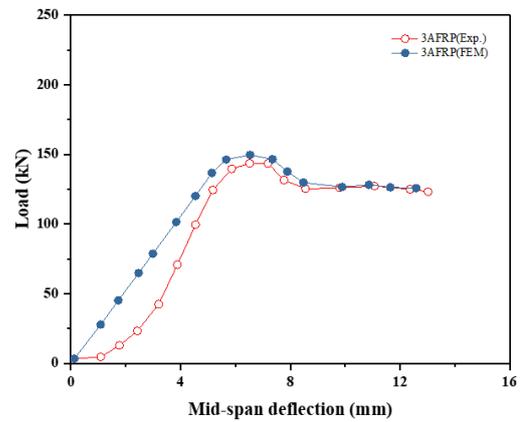
The present FE analysis results include the support reaction time history and MSD time history curves of the RCD beams. Recorded values from the FE results are presented in Table 8.



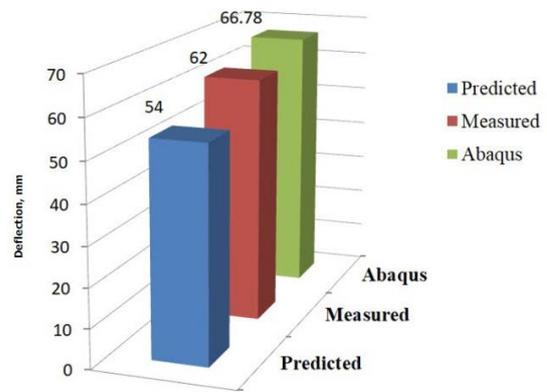
(a)



(b)



(c)



(d)

**Figure 2.** Illustrations deflection diagrams for the beams utilizing the FE model and the laboratory specimen; (a) 3CFRP beam, (b) 3GFRP beam, (c) 3AFRP beam, (d) The sample studied by Vu and Deeks (45)

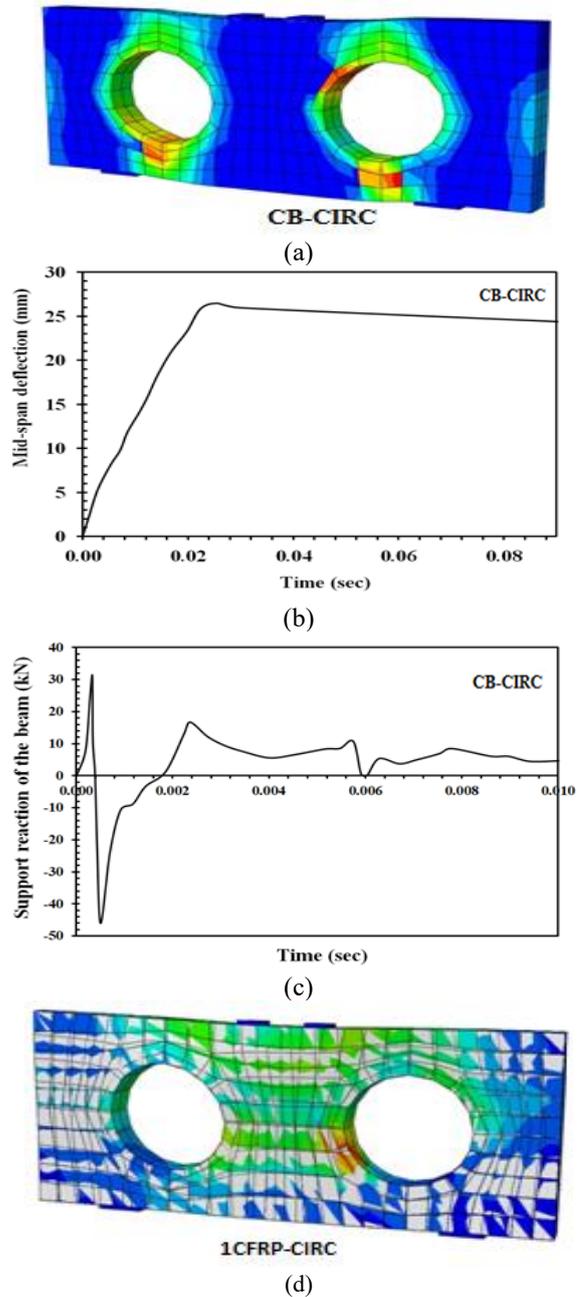
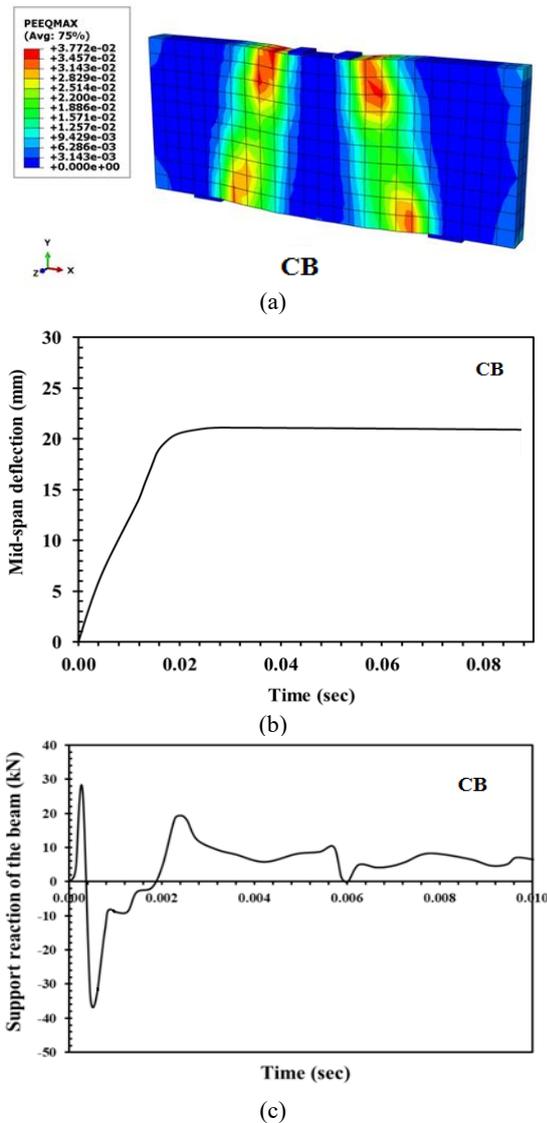
**TABLE 8.** Maximum Support Reactions and MSDs of Beams

MSD (mm)	Maximum support reaction (kN)	Beam Name	Beam No.
20.13	37.16	CB	1
26.48	46.03	CB-CIRC	2
27.81	46.6	CB-REC	3
14.45	32.12	1CFRP- CIRC	4
15.15	36.89	1CFRP- REC	5
14.70	35.88	1GFRP- CIRC	6
15.70	37.87	1GFRP- REC	7
16.23	38.28	1AFRP- CIRC	8
16.93	42.26	1AFRP- REC	9
11.40	32.31	2CFRP- CIRC	10
10.12	29.91	3CFRP- CIRC	11
9.87	28.34	4CFRP- CIRC	12

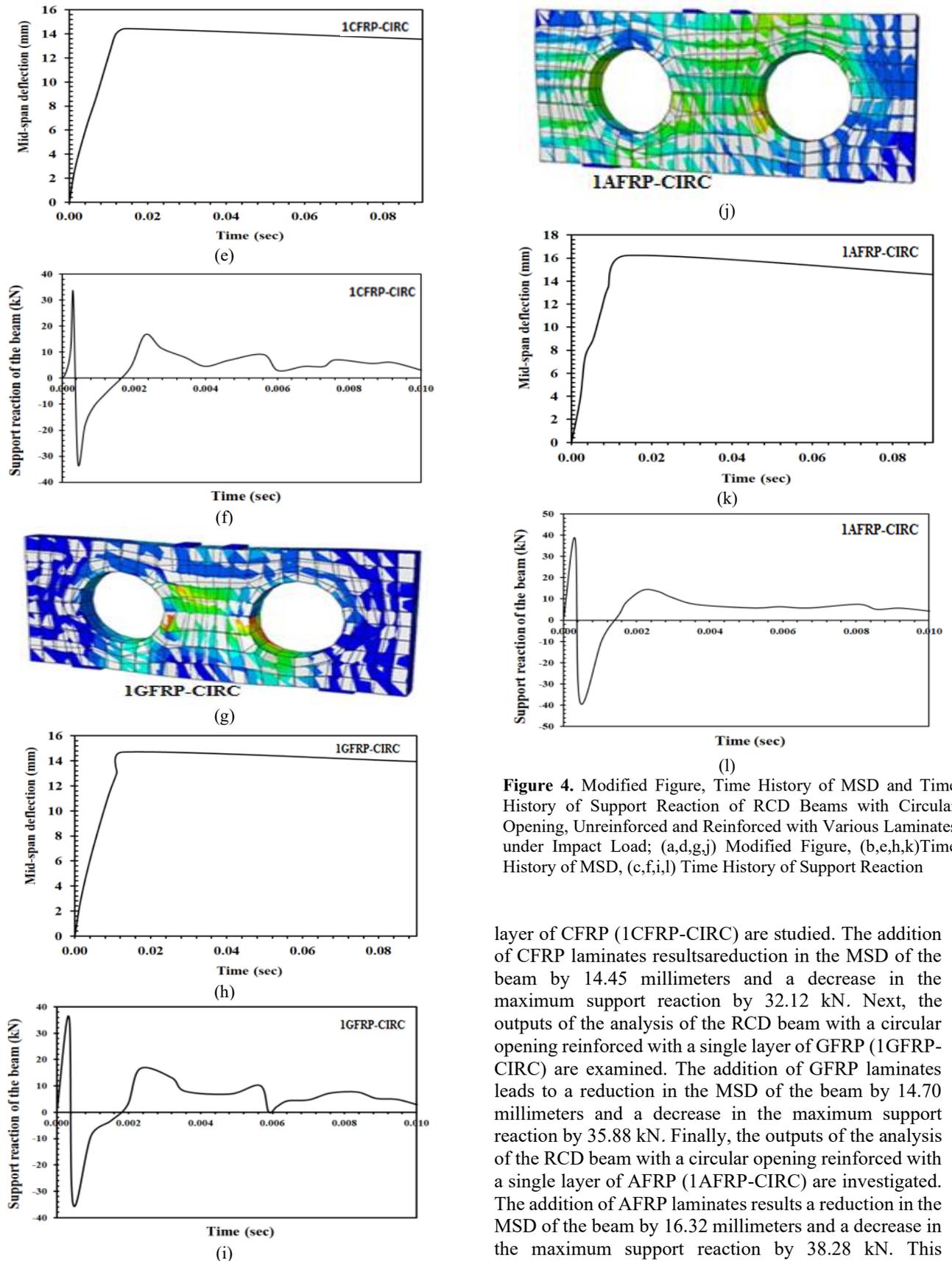
**6. 1. Control Beam without Opening** In Figure 3, the modified figure, the time history of the MSD and the time history of the support reaction of the unreinforced control beam (CB) without openings are depicted. As observed, the mid-span point of this beam has experienced a downward displacement of 20.13 millimeters due to the applied impact. Additionally, the maximum support reaction generated in the beam amounts to 37.16 kN. The cracks formed are oriented along the direction of the impact and have a vertical path.

**6. 2. RCD beams with Circular and Rectangular Openings** The results from the FE examination of RCD beams featuring circular openings, both lacking

reinforcement and enhanced with a solitary ply of CFRP, GFRP, and AFRP laminates subjected to impact loading, are depicted in Figure 4. According to this figure, initially, the outputs of the FE analysis of the unreinforced RCD beam with a circular opening (CB-CIRC) are examined. Under impact load, the MSD of the beam increases by 26.48 millimeters, and the maximum support reaction of the beam is 46.03 kN. The deformations induced in beams with circular openings are approximately 24% higher than those in beams without openings. Subsequently, the outputs of the analysis of the RCD beam with a circular opening reinforced with a single



**Figure 3.** Modified Figure, Time History of MSD and Time History of Support Reaction of Unreinforced control beam (CB) without openings under Impact Load ;(a) Modified Figure, (b) Time History of MSD, (c) Time History of Support Reaction



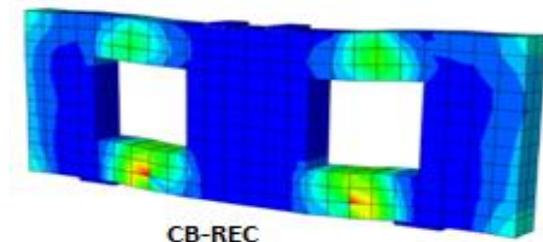
**Figure 4.** Modified Figure, Time History of MSD and Time History of Support Reaction of RCD Beams with Circular Opening, Unreinforced and Reinforced with Various Laminates under Impact Load; (a,d,g,j) Modified Figure, (b,e,h,k) Time History of MSD, (c,f,i,l) Time History of Support Reaction

layer of CFRP (1CFRP-CIRC) are studied. The addition of CFRP laminates results a reduction in the MSD of the beam by 14.45 millimeters and a decrease in the maximum support reaction by 32.12 kN. Next, the outputs of the analysis of the RCD beam with a circular opening reinforced with a single layer of GFRP (1GFRP-CIRC) are examined. The addition of GFRP laminates leads to a reduction in the MSD of the beam by 14.70 millimeters and a decrease in the maximum support reaction by 35.88 kN. Finally, the outputs of the analysis of the RCD beam with a circular opening reinforced with a single layer of AFRP (1AFRP-CIRC) are investigated. The addition of AFRP laminates results a reduction in the MSD of the beam by 16.32 millimeters and a decrease in the maximum support reaction by 38.28 kN. This

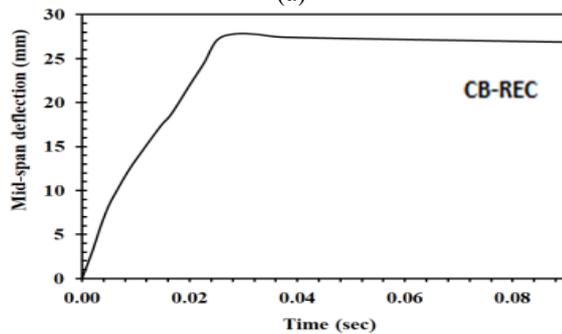
represents a 16% reduction in comparison to the unreinforced RCD beam with a circular opening.

The outputs of the analysis of RCD beams with rectangular openings, both unreinforced and reinforced with a single layer of CFRP, GFRP, and AFRP laminates under impact load are presented in Figure 5. The FE analysis results of the unreinforced and reinforced concrete deep beam, featuring two rectangular openings at the mid-span, reveal that upon application of the impact load, the MSD of the beam increases by 27.81 millimeters, and the maximum support reaction of the beam is 46.60 KN. The deformations induced in beams with rectangular openings are approximately 38% higher than those in solid beams without openings. Cracks are observed in the lower regions of the beam in a flexural manner and in the central regions in a flexural-shear manner. In another analysis, the addition of a CFRP laminate results a reduction in MSD of the beam to 15.15 millimeters. This change indicates an approximate 5% increase compared to the CFRP-reinforced circular opening deep beam. Additionally, the support reaction of the beam decreases to 36.89 KN, indicating a reduction of approximately 21% in support forces compared to the unreinforced beam with rectangular opening (CB-CIRC).

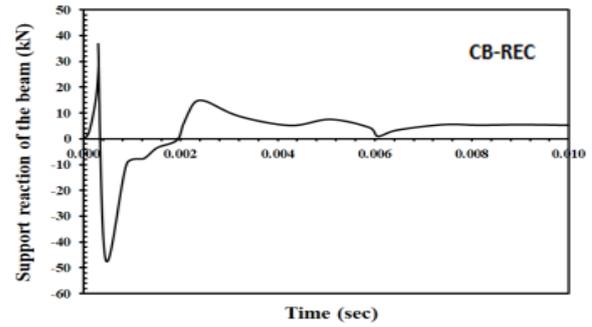
In the event of employing an un-damped SDOF configuration, the highest reaction elicited by every form of impulsive force is solely reliant on the proportion between the duration of the impulse and the inherent period of the structure (46). Hence, reinforcing beams results in elongating their inherent period, consequently diminishing the amplification factor of their dynamic reaction, leading to a subsequent reduction in the utmost response of the beams when subjected to impact loading.



(a)

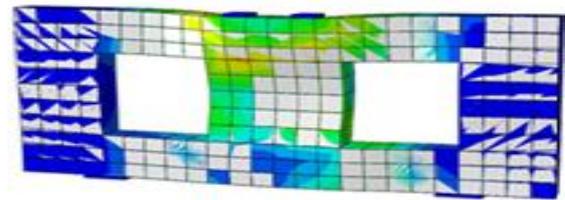


(b)



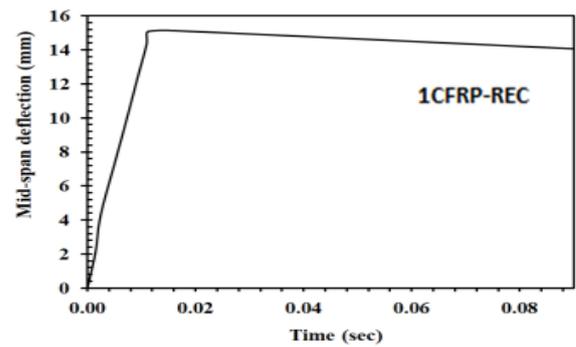
Time (sec)

(c)



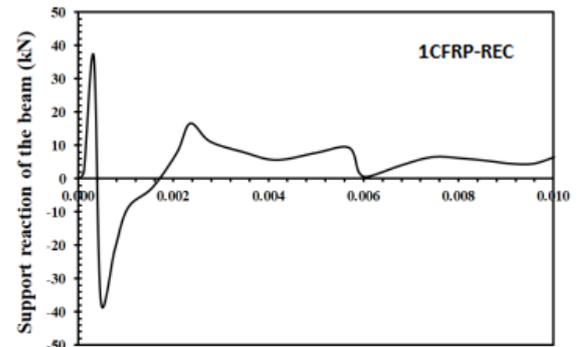
1CFRP-REC

(d)



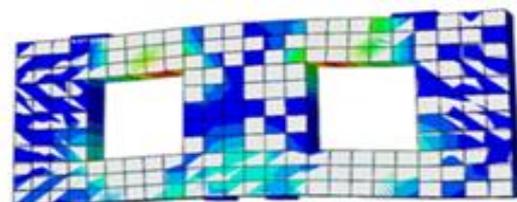
Time (sec)

(e)



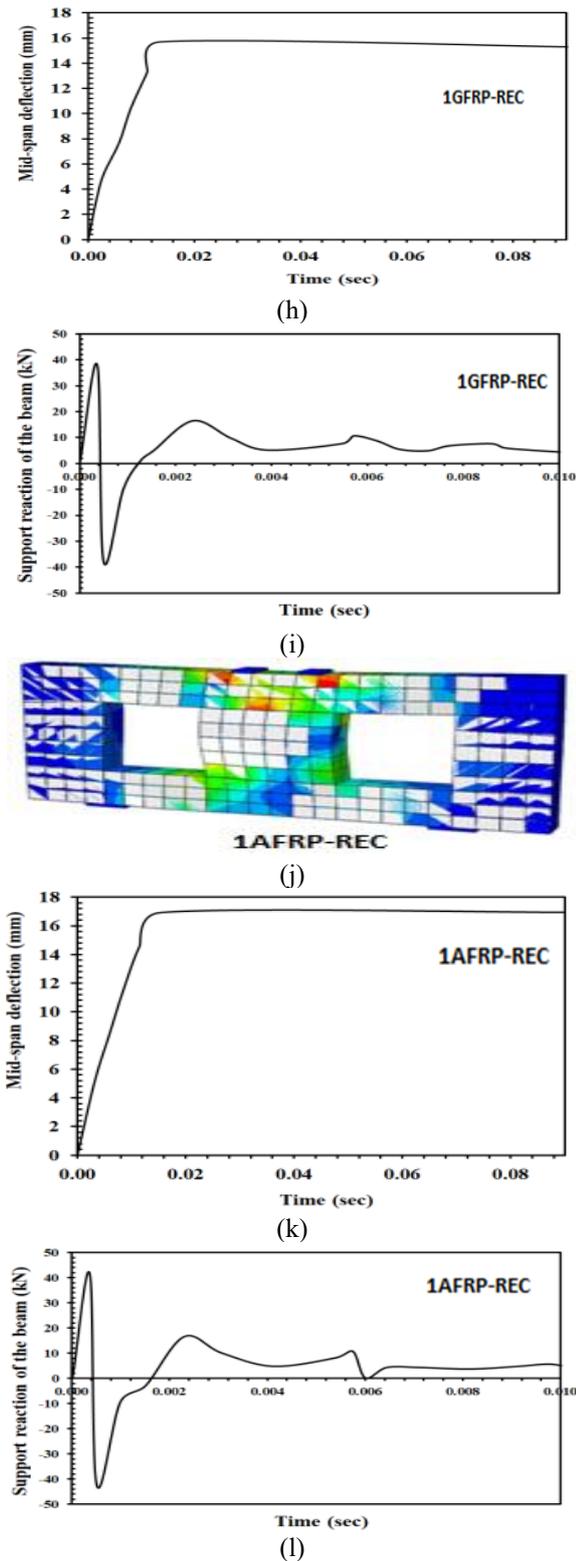
Time (sec)

(f)



1GFRP-REC

(g)



**Figure 5.** Modified Figure, Time History of MSD and Time History of Support Reaction of RCD Beams with Rectangular Opening, Unreinforced and Reinforced with Various Laminates under Impact Load; (a,d,g,j) Modified Figure, (b,e,h,k) Time History of MSD, (c,f,i,l) Time History of Support Reaction

Using GFRP laminates, the maximum displacement of the beam decreases to 15.70 millimeters, and the maximum support reaction increases to 37.87 kN. These values demonstrate proportional changes relative to the type of laminates used. Beams equipped with AFRP laminates exhibit 39% reduction in MSD compared to the control beams (CB-CIRC), accompanied by an increase in steel efficiency in redistributing forces, with their maximum support reaction reaching 42.26 kN.

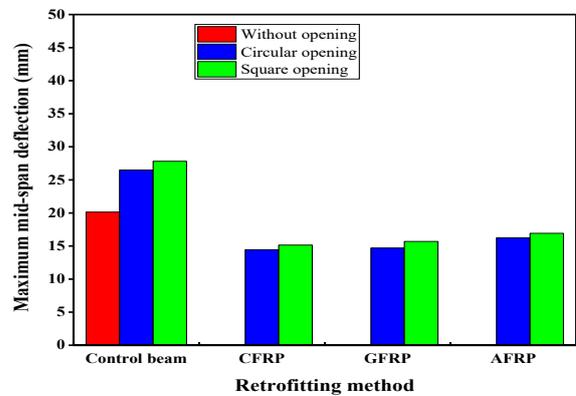
**6. 2. 1. Comparison of MSDs**

Figure 6 presents a comparison MSD of beams under impact load. It is evident that the use of all three types of FRP laminates results in a reduction in the MSD of RCD beams under impact loading. Additionally, the utilization of CFRP laminates in beams exhibits significantly better performance in terms of MSD compared to AFRP and GFRP laminates. In RCD beams with circular openings, the use of CFRP, GFRP, and AFRP laminates has led to reductions of 45%, 44%, and 39%, respectively, in MSD. Similarly, in beams with rectangular openings, the use of CFRP, GFRP, and AFRP laminates has resulted in reductions of 46%, 44%, and 39%, respectively, in maximum MSD.

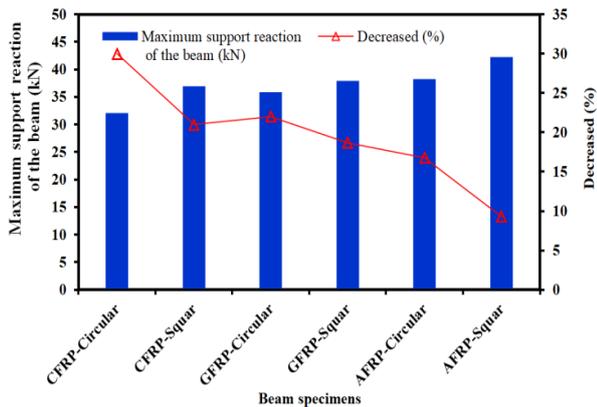
**6. 2. 2. Comparison of Support Reactions**

Figure 7 compares the maximum support reaction of beams to investigate the type of FRP laminates and the geometric shape of openings. As observed, in all cases, the use of FRP laminates leads to a reduction in support reactions. Indeed, beam reinforcement increases flexibility and ductility, which increases the natural period of the beam, resulting in a reduction in the dynamic amplification factor and, consequently, a decrease in the maximum support reaction under impact load.

In RCD beams with circular openings, adding CFRP, GFRP, and AFRP laminates has reduced the support reaction by 30%, 22%, and 16%, respectively.



**Figure 6.** Comparison MSD of beams under Impact Load for Investigating the Type of FRP Laminates and the Geometric Shape of Openings

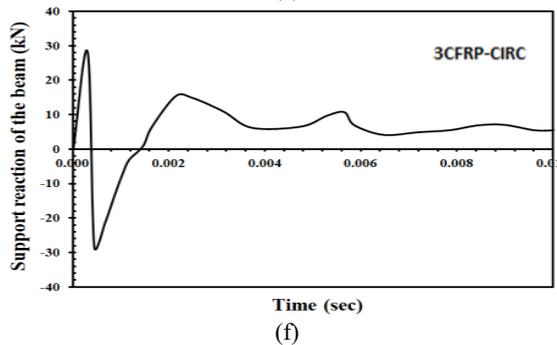
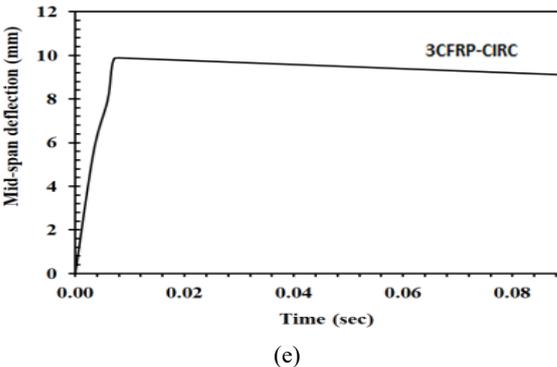
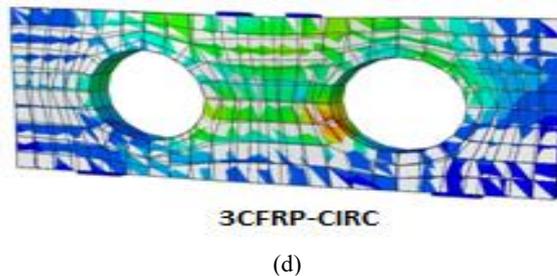
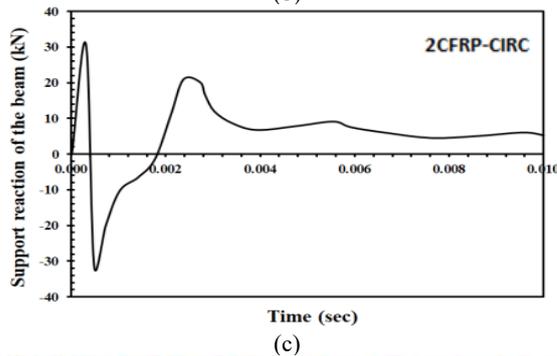
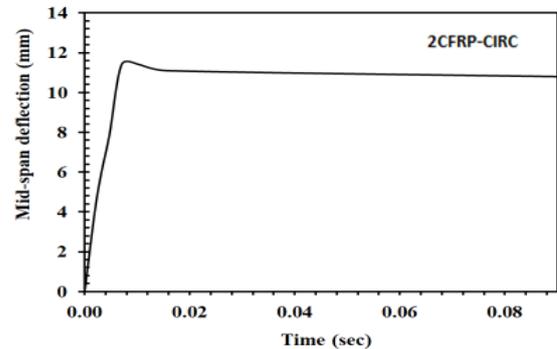
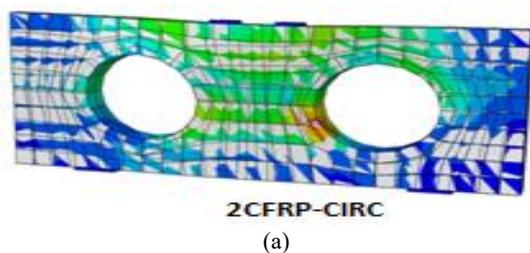


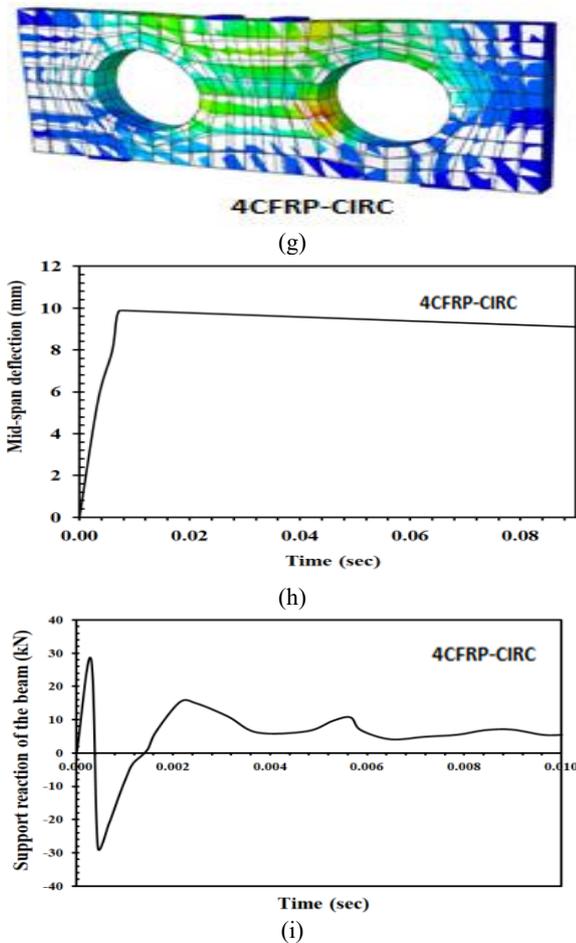
**Figure 7.** Comparison of maximum support reaction of beams and percentage reduction relative to control samples under impact load for investigating the type of FRP laminates and the geometric Shape of openings

Furthermore, in beams with rectangular openings, adding CFRP, GFRP, and AFRP laminates has reduced the support reaction by 21%, 18%, and 9%, respectively.

**6. 3. RCD Beams with Multiple Layers of CFRP**

Another factor explored in the current investigation is the impact of varying the quantity of CFRP layers on the behavior of RCD beams under impact forces. Consequently, simulations were conducted on beams featuring circular openings, reinforced with a solitary layer of CFRP, across three distinct scenarios involving 2, 3, and 4 layers of CFRP. The results are depicted in Figure 8. The analytical outcomes pertaining to RCD beams equipped with circular openings and reinforced with CFRP, under impact loading, were scrutinized. For the beam reinforced with two layers of CFRP, the MSD measured 4.11 millimeters, and the maximum support reaction recorded was 31.32 kN. Notably, it was observed that augmenting the number of CFRP layers to three resulted in a reduction of the MSD to 10.12 millimeters, while the maximum support reaction escalated to 91.29 kN. Conversely, for the beam fortified with four layers of CFRP, the MSD registered at 9.87 millimeters, with the maximum support reaction reaching 28.34 kN. These findings suggest that enhancing the quantity of CFRP layers enhances the beam's resilience against impact loading.

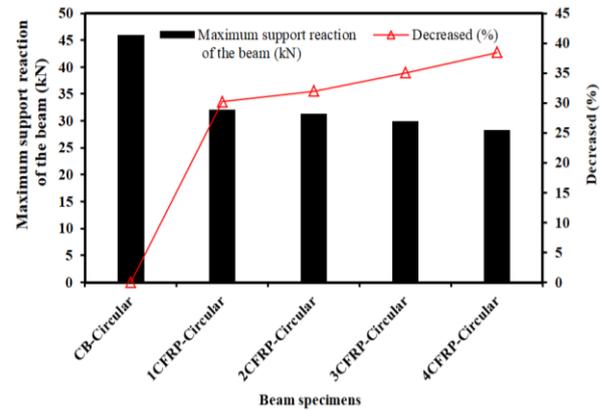




**Figure 8.** Modified figure, time history of MSD and time history of support reaction of RCD beams with circular opening, reinforced with n number of CFRP layers under impact load; (a, d, g) Modified Figure, (b, e, h) Time History of MSD, (c, f, i) Time History of Support Reaction

**6. 3. 1. Comparison of Maximum Support Reaction for Investigating the Number of Layers**

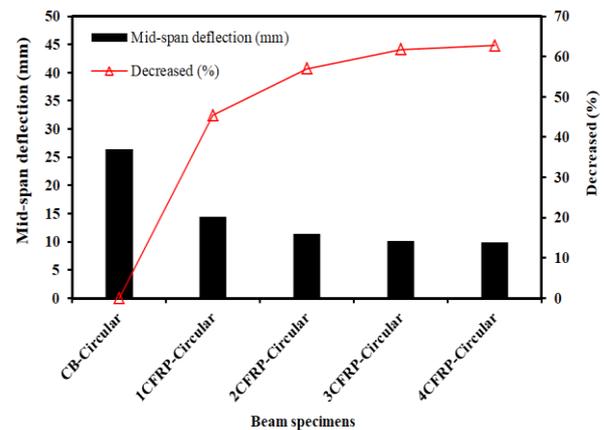
Figure 9 contrasts the utmost backing reaction for examining layer quantity. The employment of one, two, three, and four strata of CFRP layers within RCD beams under impact loads resulted in diminishing the utmost support reaction by 30%, 32%, 35%, and 38%, respectively. Raising the stratum quantity from one to four triggered only approximately an 8% descent in support reaction from impact loads. Given that adopting four strata of CFRP amplifies the expense fourfold, an 8% decrement in load-bearing capacity lacks economic justification. Integrating more strata of CFRP layers into RCD beams under impact loads confines crack spread and plastic distortions, beneficially impacting the dynamic demeanor of the beams. Moreover, heightening ductility induces an additional augmentation in the innate period of the beam, culminating in a greater diminution in dynamic response.



**Figure 9.** Comparison of maximum support reaction to investigate the number of layers

**6. 3. 2. Comparison of MSD for Investigating the Number of Layers**

Figure 10 illustrates the MSD in relation to the examination of layer quantity. With an augmentation in layer count, the MSD diminishes. Incorporating one, two, three, and four layers of CFRP laminates resulted in decreases in MSD by 45%, 56%, 61%, and 62% correspondingly. Expanding the quantity of CFRP layers not solely heightens flexibility, ductility, and the innate period of the beam, causing a decline in the dynamic amplification factor of the beam's reaction, but also curtails crack spread within the beam, leading to a reduction in MSD.



**Figure 10.** Comparison of MSD to Investigate the Number of Layers

**7. CONCLUSIONS**

In this study, the effect of beam opening shape, type and the number of FRP laminates on the MSD and maximum support reaction of RCD beams was investigated. Initially, a beam without openings was studied, then the effect of circular and rectangular openings was

examined, and finally, the influence of the type and number of FRP layers in circular openings was investigated.

The results obtained from the effect of reinforcement using CFRP, GFRP, and AFRP laminates on the dynamic behavior of RCD beams under impact loads showed that reinforcement with these laminates leads to a reduction in the MSD and the maximum support reaction. Additionally, CFRP laminates perform better than GFRP and AFRP, such that increasing the number of CFRP layers results in improved beam performance against impact loads. Furthermore, the investigations indicated that using circular openings performs better than rectangular ones in reducing the MSD and maximum support reaction. However, results showed that increasing the number of CFRP laminate layers is associated with increased costs and a significant reduction in load-bearing capacity, resulting in only an 8% reduction in the support reaction under impact loads. This point highlights the need for a more detailed examination of factors such as additional costs associated with increasing the number of layers, compared to the economic efficiency of structures and the type of openings used. Therefore, implementing reinforcement using CFRP laminates and circular openings can significantly improve the performance and stability of RCD beams under impact loads. However, a more thorough examination of costs and economic efficiency of structures is needed to fully consider these changes and make better decisions in the design and implementation of reinforced concrete structures under impact loads.

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**Persian Abstract**

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**چکیده**

این پژوهش به بررسی عملکرد دینامیکی تیرهای عمیق بتن مسلح (RCD) تحت بارهای ضربه‌ای پرداخته و به‌ویژه تأثیر روش‌های تقویت و پیکربندی‌های هندسی بازشوها بر رفتار آن‌ها را تحلیل می‌کند. در این مطالعه از تکنیک‌های تحلیل اجزای محدود (FE) برای شبیه‌سازی سناریوهای مختلف استفاده شده است که شامل انواع و تعداد متفاوتی از لایه‌های پلیمری مسلح به الیاف (FRP) و پیکربندی‌های هندسی بازشوها می‌شود. نتایج نشان می‌دهند که تقویت با لایه‌های FRP به‌طور چشمگیری تغییر شکل میانه دهانه و واکنش حداکثری تکیه‌گاهی را کاهش می‌دهد، به‌طوری‌که لایه‌های FRP کربنی (CFRP) در مقایسه با FRP آرامیدی (AFRP) و FRP شیشه‌ای (GFRP) عملکرد بهتری دارند. بازشوهای دایره‌ای نسبت به بازشوهای مستطیلی در کاهش تغییر شکل میانه دهانه و واکنش تکیه‌گاهی مؤثرتر عمل می‌کنند. با این حال، افزایش تعداد لایه‌های CFRP چالش‌های اقتصادی به همراه داشته و کاهش محدودی در ظرفیت باربری ایجاد می‌کند. این یافته‌ها بر اهمیت انتخاب دقیق استراتژی‌های تقویتی و شکل بازشوها برای بهینه‌سازی پایداری و عملکرد تیرهای عمیق بتن مسلح تحت بارهای ضربه‌ای تأکید دارند و تعادلی میان کارایی مهندسی و صرفه اقتصادی پیشنهاد می‌کنند.

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