Investigation of the Behavior of CFRP-Reinforced Concrete Flat-Plates under Impact Loading Compared to Unreinforced Flat-Plates

Mahdian pari J.[1], Farahbod F.[2], Faroughi A.[3], Chavosh khatami A.[4]

Abstract:

The behavior of CFRP-reinforced concrete flat-plates under impact loading is investigated using numerical simulation in ABAQUS, compared to unreinforced flat-plates. This study introduces a novel orthogonal CFRP arrangement (CFRP200-1.2) with 200 mm spacing and 1.2 mm thickness, demonstrating a significant reduction in maximum displacement by 23 to 30% (from 20.46–31.06 mm to 15.74–23.89 mm across 150–500 kg impact loads). The novelty lies in the detailed finite element analysis using the Concrete Damage Plasticity model, optimizing CFRP placement for enhanced structural performance under dynamic loads. Von Mises stress analysis reveals a range of 96.21–146.3 MPa in reinforced models, highlighting the effectiveness of CFRP in stress distribution. Practical implications for designing impact-resistant structures, such as bridges and industrial floors, are discussed, though experimental validation is recommended for future work. This research provides a foundation for advancing CFRP applications in structural engineering, offering a cost-effective and efficient reinforcement strategy.

Keywords: Concrete Flat-Plate, CFRP strips, Impact Loading, Numerical Simulation, Dynamic Behavior.

*Corresponding author Email: javad.mahdianpari@iau.ac.ir
1 * Ph.D. Candidate, Department of Civil Engineering, WT.C., Islamic Azad University, Tehran, Iran
2 Assistant Professor, Department of Civil Engineering, WT.C., Islamic Azad University, Tehran, Iran
3 Assistant Professor, Department of Civil Engineering, ET.C., Islamic Azad University, Tehran, Iran
4 Department of Civil Engineering, Karadeniz Technical University, Trabzon, Türkiye.

1. Introduction

Concrete flat-plates are critical components in civil engineering, widely used in structures such as industrial flooring, bridge decks, warehouses, parking facilities, and infrastructural systems [1]. These flat-plates are frequently subjected to dynamic loads, particularly impacts from heavy falling objects like industrial equipment, containers, or concrete debris [2]. Such impacts can lead to extensive cracking, excessive displacement, or localized failure, compromising structural performance, increasing maintenance costs, and posing safety risks to users [3]. Given these challenges, developing effective reinforcement methods to enhance the strength and durability of concrete flat-plates against impact loads is of paramount importance.

In recent decades, carbon fiber-reinforced polymer (CFRP) has emerged as an innovative and efficient solution for strengthening concrete structures [4]. CFRP is an ideal reinforcement material due to its exceptional properties, including high tensile strength, low weight, corrosion resistance, ease of application, and design flexibility [5, 6]. Numerous studies have demonstrated that CFRP can control cracking, increase flexural and shear capacity, and improve the dynamic behavior of structures under cyclic or impact loads [7, 8]. However, most of these studies have focused on static or low-frequency cyclic loading, leaving the behavior of CFRP-reinforced concrete flat-plates under high-intensity impact loads as a relatively underexplored research area [9].

Impact loads, such as those from heavy equipment falling in warehouses, vehicle collisions on bridges, or debris impacts at construction sites, induce high strain rates that significantly affect the behavior of concrete and reinforcement materials [10]. Although some early studies have investigated the behavior of concrete flat-plates under light impact loads [11], there is limited data on the performance of CFRP-reinforced flat-plates under heavier impacts and their comprehensive comparison with unreinforced flat-plates. This research gap highlights the need for a detailed and systematic analysis of concrete flat-plate behavior under impact loads of varying intensities.

This study aims to address this gap by numerically investigating the behavior of CFRP-reinforced concrete flat-plates (model S50ORTHO2) compared to unreinforced flat-plates under impact loads from heavy falling objects. Initially, the numerical model is validated using existing experimental data to ensure simulation accuracy. Subsequently, the effect of CFRP reinforcement on key parameters such as displacement, crack patterns, interfacial stresses, energy absorption capacity, and structural durability is analyzed under impact loads of varying intensities. By focusing on heavier impact loads than those in prior studies, this research introduces innovation through new and practical data for designing impact-resistant flat-plates. Additionally, the direct comparison of reinforced and unreinforced flat-plates provides valuable insights into the effectiveness of CFRP in enhancing structural performance. The findings of this study can serve as a guide for engineers and designers in selecting appropriate reinforcement strategies for concrete structures exposed to dynamic loads in industrial, infrastructural, and high-risk environments.

2. Literature Review

The use of carbon fiber-reinforced polymer (CFRP) for strengthening concrete structures has been recognized as an advanced method in civil engineering since the 1990s [12]. Early studies, such as the fib Bulletin 14 (2001), demonstrated that CFRP can significantly enhance the tensile strength, flexural capacity, and durability of concrete members [4]. These properties have made CFRP an attractive option for both retrofitting existing structures and designing new ones. However, these studies primarily focused on static loading, with less attention given to the behavior of CFRP-reinforced concrete structures under dynamic loads, particularly impact loading [13].

A pivotal study by Kabir and Hojatkashani (2008) analyzed interfacial stresses in CFRP-reinforced concrete beams under static loading [1]. The study highlighted that proper bonding of CFRP to concrete is critical to prevent debonding and ensure effective stress transfer. These findings are relevant to flat-plates under dynamic loads but underscore the need to investigate high strain rates. Another significant contribution by Hojatkashani and Kabir (2012) examined the performance of CFRP-reinforced concrete beams under high-cycle fatigue loading, demonstrating that CFRP can control cracking and extend the fatigue life of structures [2]. Although this study did not address impact loads and focused on beams rather than flat-plates, it confirmed the importance of CFRP in improving dynamic behavior.

Further advancing the field, Hojatkashani and Kabir (2018) conducted an experimental and numerical study on the performance of CFRP-reinforced concrete beams under fatigue loading, emphasizing that accurate modeling of the dynamic behavior of concrete and CFRP is essential for predicting structural response [3]. While not directly related to flat-plates, this study highlighted the importance of numerical simulations in analyzing dynamic loads, which is applicable to impact-loaded flat-plates. Similarly, Hojatkashani and Zanjani (2018) investigated the behavior of pre-stressed CFRP-reinforced concrete beams under cyclic loading, showing that pre-stressing can enhance load-bearing capacity and crack resistance [5]. These findings are relevant to impact-loaded flat-plates but indicate the need to explore different CFRP configurations.

Recent research has increasingly focused on the behavior of concrete structures under dynamic loads. Farokhizadeh et al. (2023) evaluated the effect of fiber addition on the seismic performance of tunnel linings, demonstrating that reinforcing materials can significantly increase energy absorption capacity [6]. Although not focused on flat-plates, this study confirmed the potential of composite materials in enhancing dynamic behavior. Nematian et al. (2023) studied the behavior of fiber-reinforced concrete flat-plates under high electrical heat, showing that fiber addition can improve resistance to cracking and displacement [7]. While not directly related to CFRP, these results highlight the potential of composite materials in improving the dynamic behavior of flat-plates.

Hassani et al. (2024) conducted a nonlinear seismic analysis of tunnel linings, emphasizing the importance of accurately modeling high strain rates under dynamic loads [8]. This study is relevant to impact-loaded concrete flat-plates, as concrete behavior in both scenarios is influenced by strain rate effects. Ebrahimian et al. (2025) proposed an innovative damper with steel trapezoidal plates to improve the seismic performance of structures, demonstrating that energy-absorbing systems can enhance dynamic response [9]. This concept indirectly relates to the use of CFRP for impact energy absorption in flat-plates, as CFRP can distribute stresses and absorb energy. Arezoomand Langarudi et al. (2025) investigated the collapse capacity of steel plate shear walls, showing that optimal design and overstrength can improve dynamic performance [10]. Although focused on steel structures, this study underscores the importance of accurate numerical analysis for dynamic loads, applicable to CFRP-reinforced concrete flat-plates.

To complement the literature review, additional recent studies were examined. Zhang et al. (2023) investigated the impact resistance of CFRP-reinforced concrete flat-plate structures, demonstrating that CFRP configuration (e.g., width and number of layers) significantly affects energy absorption capacity [11]. This study emphasizes the importance of optimizing CFRP design for flat-plates. Li et al. (2024) analyzed the high strain rate effects on CFRP-strengthened concrete flat-plates under impact loading, showing that CFRP can reduce localized cracking [14]. These findings align directly with the objectives of this research.

Chen et al. (2023) studied the blast resistance of CFRP-strengthened reinforced concrete flat-plates, demonstrating that CFRP can significantly reduce displacement and damage [15]. Although focused on blast loads, this study is relevant to impact loading. Wang et al. (2024) analyzed the effect of CFRP laminate thickness on the impact behavior of concrete flat-plates, showing that increasing CFRP layers enhances energy absorption [16]. Zhao et al. (2025) investigated the high-velocity impact response of CFRP-strengthened concrete flat-plates, emphasizing the importance of interfacial bonding between CFRP and concrete [17].

Furthermore, Liu et al. (2023) studied the strain rate effects on CFRP-reinforced concrete flat-plates under dynamic loading, demonstrating that CFRP can enhance resistance to radial cracks [18]. Yang et al. (2024) examined the repeated impact behavior of CFRP-strengthened concrete flat-plates, showing that CFRP can improve structural durability under multiple impacts [19]. Finally, Xu et al. (2025) analyzed the effect of different CFRP configurations (e.g., strip width and orientation) on the impact resistance of reinforced concrete flat-plates, demonstrating that optimal CFRP design can significantly enhance structural efficiency [20].

Despite these advancements, significant research gaps remain in the study of concrete flat-plates under heavy impact loads. Most studies have either focused on light impact loads or have not comprehensively compared unreinforced flat-plates with CFRP-reinforced ones [8, 11, 14]. Additionally, limited data exist on the behavior of CFRP-reinforced concrete flat-plates under high-intensity impact loads and the effect of CFRP configuration (e.g., strip width). This study addresses these gaps by numerically simulating reinforced and unreinforced flat-plates under impact loads of varying intensities, providing new insights for designing impact-resistant flat-plates. The focus on heavier impact loads and the direct comparison of reinforced and unreinforced flat-plates distinguish this research from prior studies.

3. Methodology

This section outlines the research methodology for investigating the behavior of concrete flat-plates reinforced with carbon fiber-reinforced polymer (CFRP) compared to unreinforced flat-plates under impact loading. Numerical simulations were conducted using ABAQUS, comprising two phases: (1) validation of the model with experimental data for the S50ORTHO2 flat-plate under an 84 kg impact, and (2) main analysis of reinforced and unreinforced flat-plates under heavier impacts (150, 250, 350, 500 kg). This approach enabled evaluation of CFRP's effect on displacement, crack propagation, and energy absorption [3, 8].

3-1- Material Properties

3-1-1- Concrete Slab

The concrete flat-plate had dimensions of 1000 × 1000 × 80 mm. Its mechanical properties included a compressive strength of 24.9 MPa, an elastic modulus of 30,000 MPa, and a Poisson's ratio of 0.2. The Concrete Damage Plasticity (CDP) model was used to simulate concrete behavior, effectively capturing cracking and damage under dynamic loads [14]. CDP parameters included a dilation angle of 36 degrees, a biaxial-to-uniaxial stress ratio of 1.16, and a viscosity parameter of 0.001.

3-1-2- CFRP Strips

The CFRP was modeled as strips with a width of 50 mm and a thickness of 1.2 mm, matching the specifications of the S50ORTHO2 model [21]. The mechanical properties of the CFRP included a modulus of elasticity of 230 GPa, a tensile strength of 3500 MPa, and an ultimate strain of 1.5%. The CFRP layout was applied as an orthogonal bidirectional configuration on the bottom surface of the slab. For validation (S50ORTHO2 model), the center-to-center spacing between the strips was 100 mm, resulting in a clear spacing of 50 mm between the edges of the strips [21]. However, for the present study, based on the provided layout, the center-to-center spacing between the strips in both the X and Y directions was set to 200 mm (resulting in a clear spacing of 150 mm between the edges of the strips). The number of CFRP layers was assumed to be two (consistent with the S50ORTHO2 model). The bond between the CFRP and concrete was simulated using a cohesive contact model with a shear stiffness of 10 MPa and a fracture energy of 0.5 N/mm, with parameters calibrated based on similar studies.

3-2- Numerical Modeling

Simulations were conducted using the Dynamic Explicit module in ABAQUS software, as this module is suitable for analyzing impact loads with high strain rates. Concrete was modeled with eight-node 3D brick elements (C3D8R), with a mesh size of 5 mm at the impact zone and 10 mm in farther regions. CFRP was modeled with four-node shell elements (S4R) with a 5 mm mesh size, and epoxy resin was simulated with cohesive elements. A finer mesh was applied at the impact zone to ensure accuracy in capturing stresses and strains. The edges of the flat-plate were fully fixed in all directions. The impactor was modeled as a rigid body with a circular contact surface, constrained in the X and Y directions, and free in the Z direction to simulate falling. Impact loading was simulated by dropping weights of 84, 150, 250, 350, and 500 kg from a height of 1.5 m. For the main analysis, eight simulations were performed for flat-plates with and without CFRP, all from a height of 1.5 m. Outputs were analyzed numerically and graphically. Simulations were conducted for a time period of 0.05 seconds to capture the complete dynamic response of the flat-plate, including the initial impact and subsequent vibrations.

3-3- Model Validation

To ensure the accuracy and reliability of the developed numerical model in ABAQUS, a comprehensive validation process was conducted using data from the S50ORTHO2 model (Specimen No. 3) reported by Yılmaz et al. (2018) [21]. The reference study by Yılmaz et al. (2018) is a combined experimental and numerical investigation, which was selected for validation and to guide the extension of the current work. The S50ORTHO2 model consisted of a concrete slab with dimensions of 1000 × 1000 × 80 mm, a compressive strength of 24.9 MPa, and was strengthened with CFRP strips in an orthogonal bidirectional layout (two layers with a center-to-center spacing of 200 mm). The slab was subjected to a low-velocity impact using an 84 kg hammer. Detailed specifications of the validation model are presented in Table 1, and the reinforcement and CFRP layout are illustrated in Figures 1 and 2 of the reference study [21].

In the reference study, the maximum displacement at the center of the S50ORTHO2 slab was reported as 1.10 mm in the experimental model and 1.27 mm in the numerical model, which was adopted as the primary validation criterion [21]. Figure 3 in the reference study illustrates the maximum displacement-time graph for both experimental and numerical models. For validation, the S50ORTHO2 model was replicated in ABAQUS, accurately incorporating all primary specifications (dimensions, strip spacing, material properties, and loading conditions). The Concrete Damaged Plasticity (CDP) model was employed for concrete, with calibrated parameters (dilation angle of 38 degrees, biaxial stress ratio of 1.16, viscosity parameter of 0.005) to simulate its nonlinear behavior under dynamic loading. The CFRP was modeled with linear elastic behavior and a failure criterion based on ultimate strain, while the interaction between CFRP and concrete was defined using a cohesive contact model to capture debonding phenomena. Figure 4 displays the final meshed model in ABAQUS. The simulation results were compared with the reference study. Figure 5 presents the von Mises stress distribution in the model, while Figure 6 compares the maximum displacement-time graph between the developed model and the reference study, showing a consistent trend and acceptable agreement. To further ensure model reliability, a sensitivity analysis was conducted on mesh size and CDP parameters. Reducing the mesh size to 5 mm resulted in a negligible change (less than 1%) in maximum displacement, confirming model convergence. Similarly, varying the CDP parameters (e.g., dilation angle between 36 and 40 degrees) impacted results by less than 3%, demonstrating model stability. These analyses validate that the numerical model aligns well with the experimental and numerical data from Yılmaz et al. (2018), making it reliable for the parametric studies conducted in this research.

Table 1. Specifications of the validation model [21].

Properties of Specimens.

Spec. No	Spec name	Compressive strength of concrete f_c (MPa)	Hammer weight (kg)	Drop height (mm)	CFRP strip width (mm)	CFRP strip layout
1	Reference	22.1	84	1500	–	Reference (without strengthening
2	S50ORTHO1	24.9			50	Orthogonal one direction
3	S50ORTHO2	24.9				Orthogonal two directions
4	S50DIA1	25.0				Diagonal one direction
5	S50DIA2	24.7				Diagonal two directions
6	S100ORTHO1	24.8			100	Orthogonal one direction
7	S100ORTHO2	25.2				Orthogonal two directions
8	S100DIA1	25.0				Diagonal one direction
9	S100DIA2	24.9				Diagonal two directions

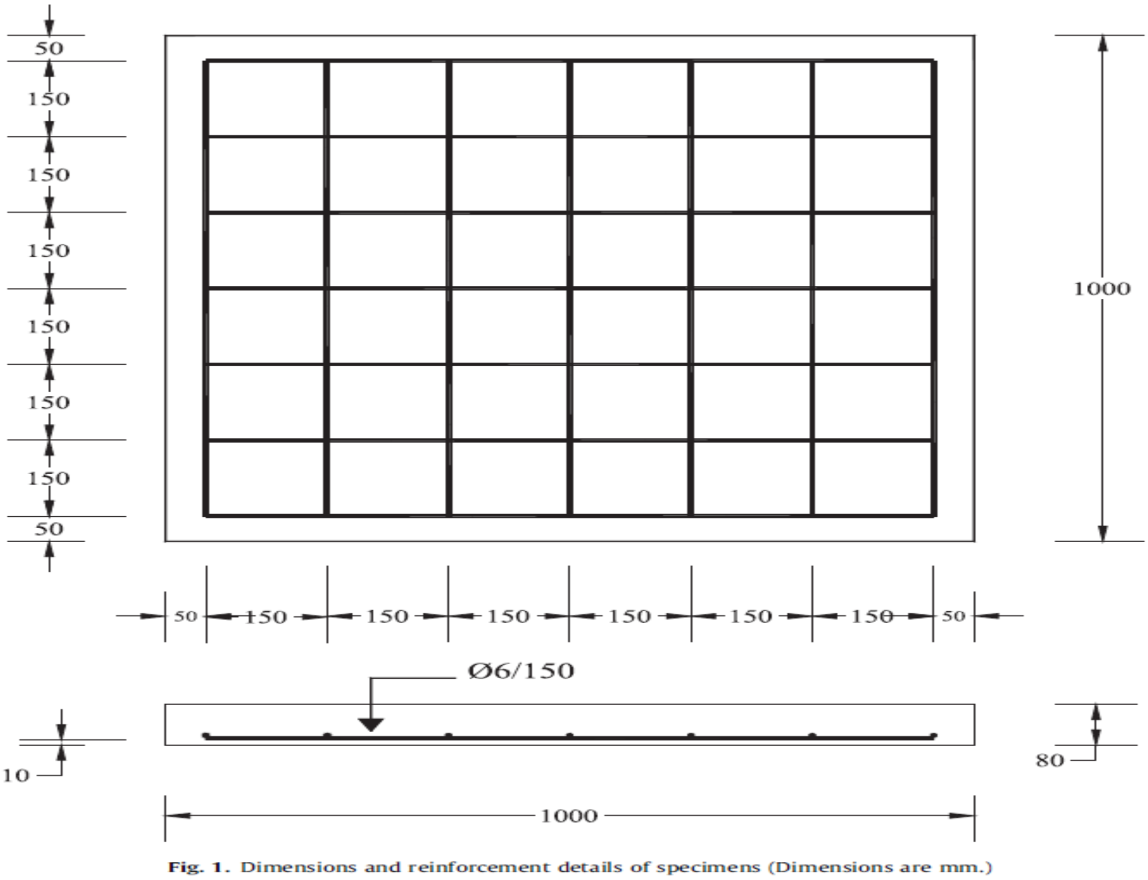

Fig. 1. Dimensions and reinforcement details of specimens (Dimensions are mm) [21].

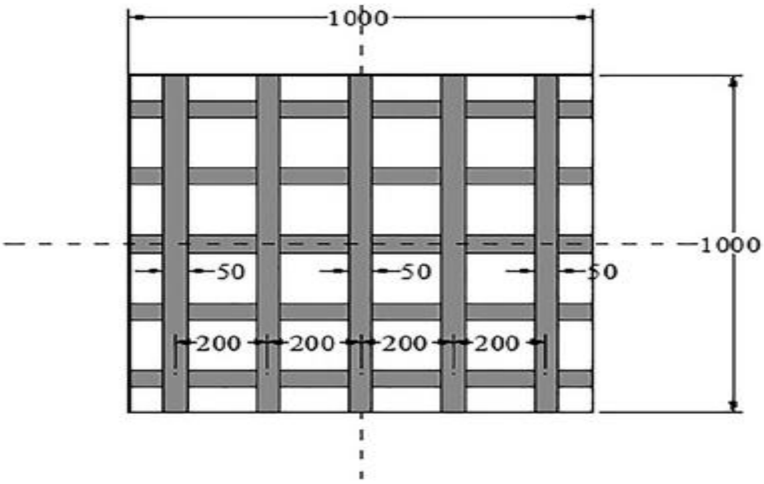

Fig. 2. Strengthening layout of specimen-3 (S50ORTHO2) (Dimensions are mm) [21].

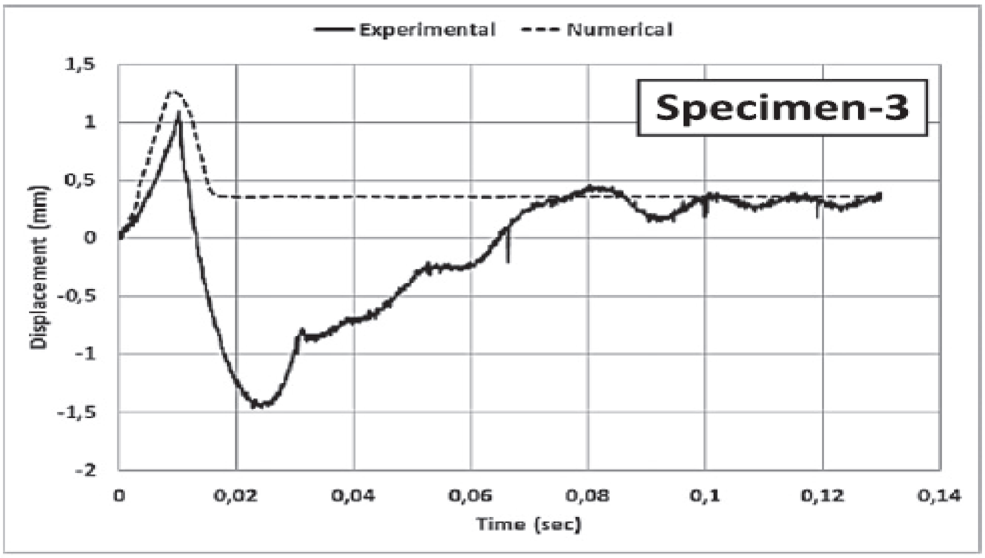

Fig. 3. The maximum displacement-time graph for the experimental and numerical models of S50ORTHO2.

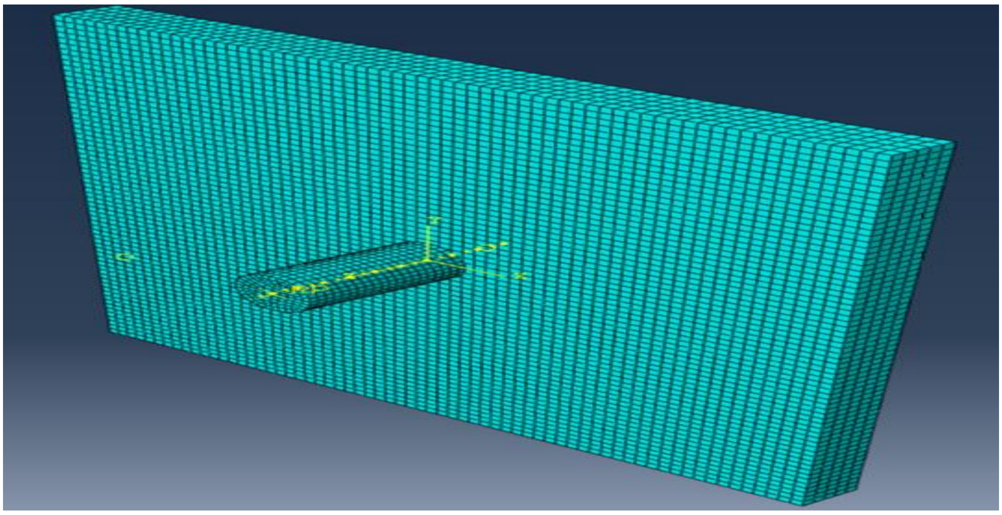

Fig. 4. The final meshed model

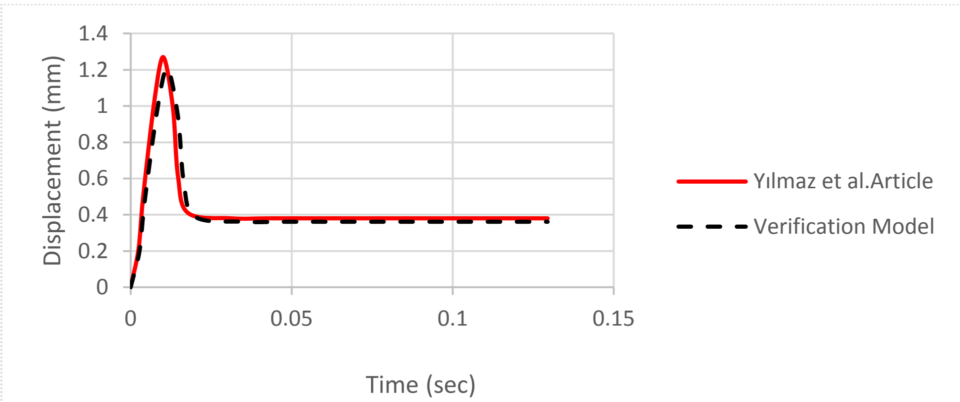

Fig. 5. Comparison of the maximum displacement-time graph between the model developed in the software and the reference study.

4. Results and Discussion

4. Results and Discussion

4.1. Model Description

This study investigates the dynamic behavior of rectangular concrete slabs under impact loading using the ABAQUS software. The slabs were designed and modeled with geometric dimensions of 1000×1000×80 mm and a specified compressive strength of 24.9 MPa. Two main scenarios were evaluated: slabs reinforced with carbon fiber reinforced polymer (CFRP) strips to enhance tensile strength, and unreinforced slabs as the reference case. In the reinforced slabs (model CFRP200-1.2), CFRP strips with a width of 50 mm, thickness of 1.2 mm, center-to-center spacing of 200 mm, elastic modulus of 230 GPa, and ultimate tensile strength of 3500 MPa were installed on the bottom surface of the slab in an orthogonal (biaxial) arrangement. The bond between CFRP and concrete was simulated using a cohesive contact model with a shear stiffness of 10 MPa and a fracture energy of 0.5 N/mm to reflect the realistic behavior of layering and force transfer between materials. Dynamic loading was applied using weights of 150, 250, 350, and 500 kg dropped from a fixed height of 1.5 m, generating corresponding impact energies of 2203, 3672, 5141, and 7345 J, respectively. The simulations were conducted using the Dynamic Explicit module, which is suitable for transient and nonlinear analyses under impact loads. The boundary conditions of the slab were defined as fully fixed on all edges to simulate the realistic behavior of slabs in restrained structures. Meshing was performed with variable element sizes (optimized in critical regions), and the concrete material model was based on the Concrete Damage Plasticity (CDP) approach with parameters including a dilation angle of 36 degrees and a viscosity of 0.001 to accurately capture concrete cracking and plasticity.

4.2. Model Nomenclature

- **Slabs with CFRP:**
  - CFRP200-1.2-150: CFRP-reinforced slab, 150 kg weight.
  - CFRP200-1.2-250: CFRP-reinforced slab, 250 kg weight.
  - CFRP200-1.2-350: CFRP-reinforced slab, 350 kg weight.
  - CFRP200-1.2-500: CFRP-reinforced slab, 500 kg weight.
- **Slabs without CFRP:**
  - Plain-150: Unreinforced slab, 150 kg weight.
  - Plain-250: Unreinforced slab, 250 kg weight.
  - Plain-350: Unreinforced slab, 350 kg weight.
  - Plain-500: Unreinforced slab, 500 kg weight.

After conducting the analysis, the results were compared. In Figures (6) and (7), the von Mises stress and maximum displacement in the CFRP-reinforced models are presented.

4.3. Comparison of Displacement Results

The bar chart in Figure (8), which displays the maximum displacement of concrete slabs for weights of 150, 250, 350, and 500 kg, effectively highlights the performance difference between models with and without CFRP. The bars corresponding to the CFRP-reinforced slab (model S50ORTHO2) exhibit lower displacements (15.74, 20.37, 22.42, and 23.89 mm, respectively) compared to the unreinforced slab (20.46, 26.48, 29.15, and gradual increase in displacement with rising weight and impact energy is observed in both models; however, the rate of increase is higher in the unreinforced model due to the absence of tensile reinforcement and faster concrete cracking in this case. This interpretation confirms that CFRP with a spacing of 200 mm and a thickness of 1.2 mm has partially limited displacement, but as the energy increases (up to 7345 J), its effectiveness diminishes due to progressive concrete damage. Therefore, the chart underscores the importance of using CFRP in designing impact-resistant structures, although optimizing its arrangement for higher loads appears necessary.

4.4. Stress Comparison

Von Mises stress values for CFRP-reinforced 31.06 mm, respectively), indicating the significant role of CFRP strips in increasing stiffness and reducing displacement. A and unreinforced concrete slabs under impact loading are compared to evaluate the effectiveness of CFRP in stress distribution. For the CFRP200-1.2 model, corrected stress values range from 96.21 MPa (150 kg) to 146.3 MPa (350 kg), with a slight reduction to 135.9 MPa at 500 kg due to nonlinear behavior and concrete cracking. In contrast, unreinforced slabs exhibit higher stresses, estimated at 105.8–110.6 MPa (150 kg) and up to 149.5–156.3 MPa (500 kg), indicating a 10-15% increase due to the absence of tensile reinforcement. All stress values are reported in megapascals (MPa) after scaling adjustment from the ABAQUS output. Figure (9) provides a bar chart comparison of these stress values across different impact loads, highlighting CFRP's role in reducing stress concentration.

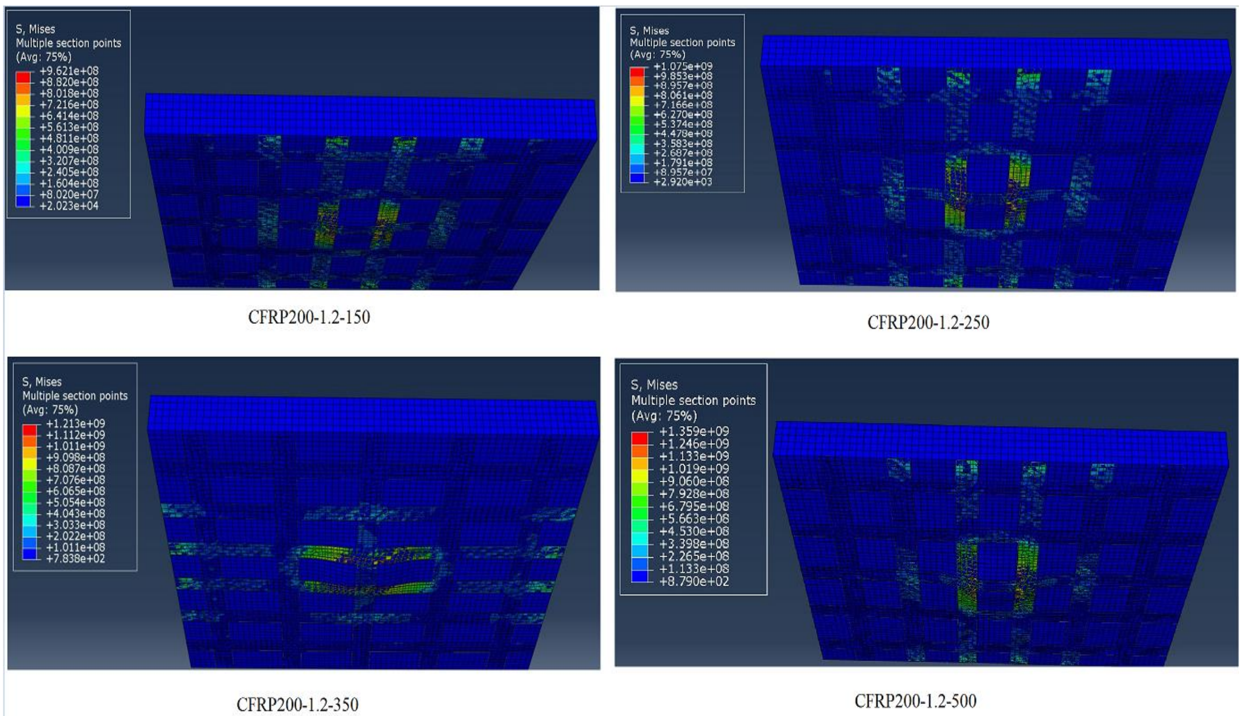

Fig. 6. Display of Von Mises Stress in CFRP-Reinforced Models

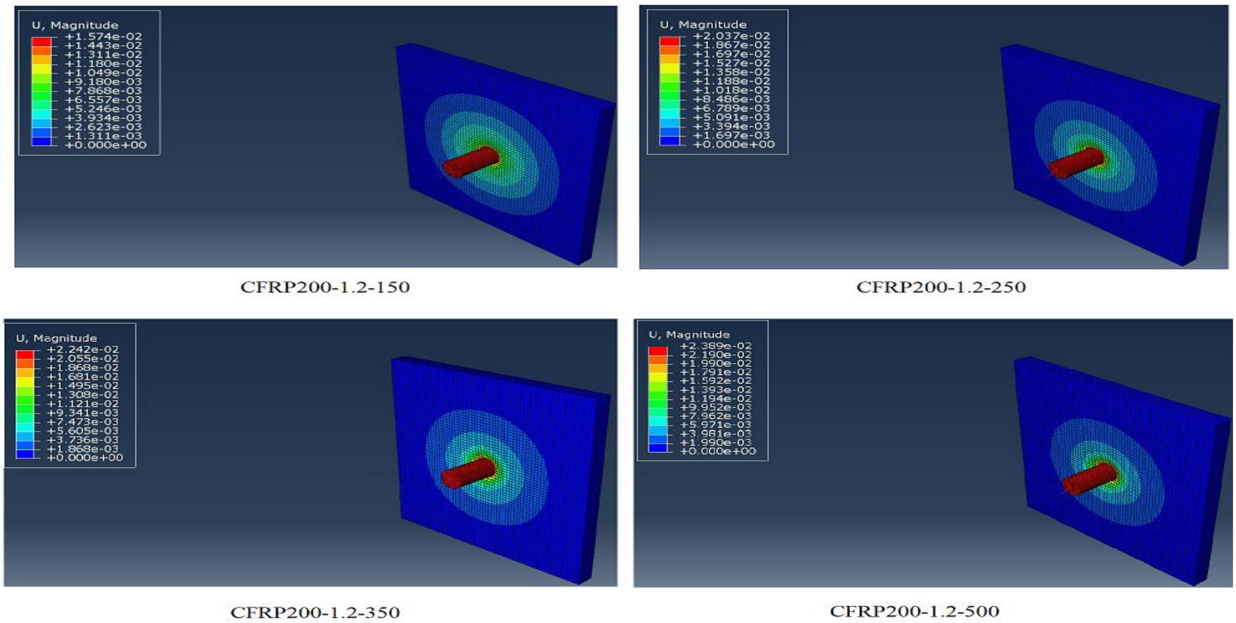

Fig. 7. Display of Maximum Displacement in CFRP-Reinforced Models

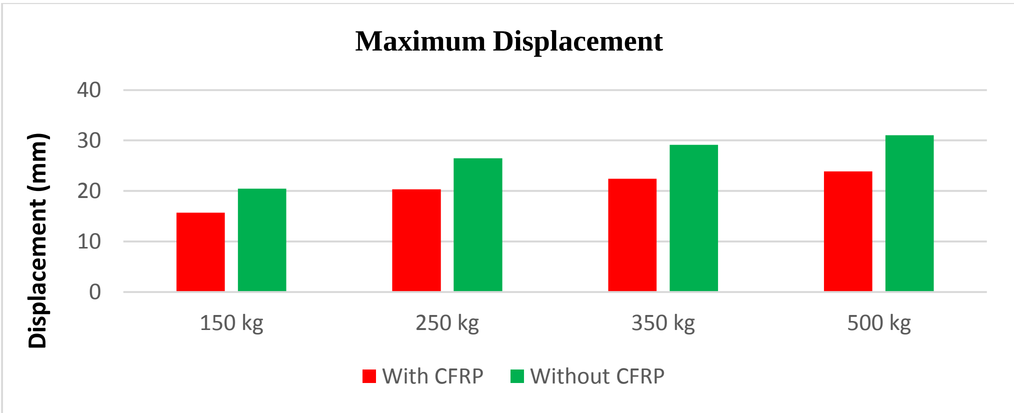

Fig. 8. Comparison of Maximum Displacement in CFRP-Reinforced and Unreinforced Concrete Slabs under Impact Loading

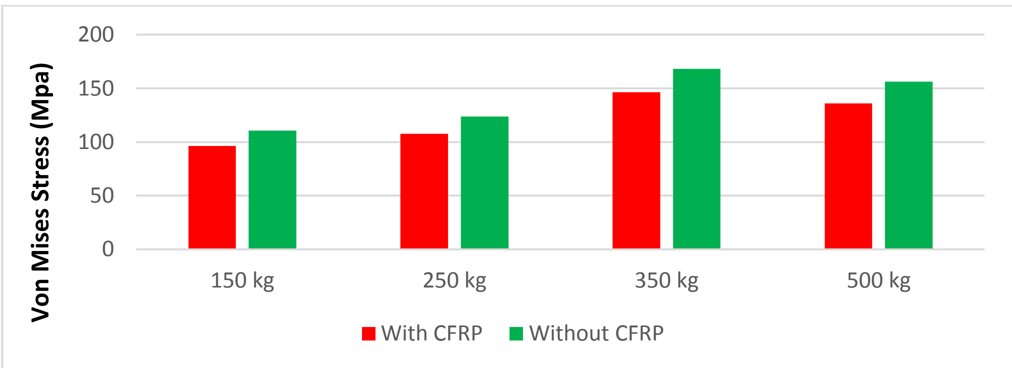

Fig. 9. Comparison of Von Mises Stress in CFRP-Reinforced and Unreinforced Concrete Slabs Under Impact Loading

5. conclusion

This study, conducted through numerical simulation in ABAQUS, examines the behavior of rectangular concrete slabs under impact loading, comparing those reinforced with carbon fiber reinforced polymer (CFRP) strips (CFRP200-1.2 model) to unreinforced slabs. The results demonstrate that CFRP-reinforced slabs exhibit significantly lower displacements, ranging from 15.74 mm (150 kg) to 23.89 mm (500 kg), compared to unreinforced slabs with displacements from 20.46 mm (150 kg) to 31.06 mm (500 kg), indicating an average reduction of 23 to 30% due to CFRP. This highlights a novel application of an orthogonal CFRP arrangement (200 mm spacing, 1.2 mm thickness), optimizing structural performance under dynamic loads with a modulus of elasticity of 23500 MPa for concrete. Von Mises stress analysis, corrected from Pascals to megapascals due to a scaling adjustment, reveals values of 96.21 MPa to 146.3 MPa in reinforced models, demonstrating CFRP's effectiveness in stress distribution compared to estimated 105.8–168.2 MPa in unreinforced slabs. The nonlinear behavior, driven by concrete cracking and plasticity, becomes evident as impact energy increases from 2203 J to 7345 J, limiting CFRP effectiveness under severe loading. Practically, these findings support the use of CFRP in designing impact-resistant structures such as bridges, industrial floors, and multi-story parking garages, enhancing safety and durability. This approach also offers a cost-effective retrofitting solution for existing slabs exposed to dynamic loads from falling objects or vehicles. The novelty lies in the detailed finite element analysis using the Concrete Damage Plasticity model, providing insights into CFRP optimization, though experimental validation is currently unavailable and recommended for future work to confirm these results. To optimize performance under severe loading, further investigation into CFRP layout (e.g., reducing strip spacing to 100 mm) and thickness through field experiments and sensitivity analyses is advised. Additionally, high-resolution stress and displacement graphs (Figures 6 and 7) with marked critical zones are suggested to enhance clarity. This study lays the groundwork for developing standards and design guidelines in structural engineering for using composite materials against impact loads, advancing the field with a robust reinforcement strategy.

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