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Article

Failure Modes Behavior of Different Strengthening Types of RC Slabs Subjected to Low-Velocity Impact Loading: A Review

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Abstract: Concrete is brittle; hence, it is incredibly likely that concrete buildings may fail in both local and global ways under dynamic and impulsive stresses. An extensive review investigation was carried out to examine reinforced concrete (RC) slab behavior under low-velocity impact loading. Significant past research studies that dealt with experimental and numerical simulations and analytical modeling of the RC slabs under impact loading have been presented in this work. As a result, numerous attempts to define failure behavior and to assess concrete structures' vulnerability to lateral impact loads have been made in the literature. Based on analytical, numerical, and experimental studies carried out in previous research, this article thoroughly reviewed the current state of the art regarding the responses and failure behaviors of various types of concrete structures and members subjected to low-velocity impact loading. The effects of different structural and load-related factors were examined regarding the impact strength and failure behavior of reinforced concrete slabs reinforced with various types of strengthening procedures and exposed to low-velocity impact loads. The reviews suggested that advanced composite materials, shear reinforcement, and hybrid techniques are promising for effectively strengthening concrete structures.

Keywords: impact behavior; failure modes; reinforced concrete; slabs; high-performance concrete

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1. Introduction

Concrete is the most extensively used material on earth after water [1–4]. Globally, reinforced concrete structures are broadly constructed due to the beneficial properties of concrete, such as high ductility [5], low thermal expansion [6,7], high stiffness [2,7]. Concrete structures also require low maintenance [8], have increased fire resistance [9,10]. They have high compressive strength but are significantly lacking in tensile strength, therefore steel is positioned in the concrete to enhance the tensile strength of the concrete [6–12]. Concrete incorporated with steel is labeled reinforced concrete (RC). Structural members, such as beams, columns, and slabs, are often subjected to sudden impact loadings in the service life of the structural element [13,14]. Impact loadings may occur because of natural hazards such as landslides, floods, earthquakes [15], heavy objects or rockfalls on the concrete slab [16], as well as vehicle collisions with piers, that cause damage to concrete structures [17,18]. Reference [19] claimed that explosions caused impact loading and significantly damaged concrete structures. Although the accidental collision or effect of the dynamic impact loading in concrete structures rarely occurs, it could be catastrophic [19]. Impact loading is different from static and dynamic loads by nature [20]; it quickly affects structural members in huge magnitudes, leading to unusual behaviors due to the strain rate effect. Compared with other loading types, impact loading is a sudden dynamic loading in nature with very high intensity [19]. Therefore, during the designing of structural components, impact loading is disregarded among structural engineers [20,21]. As a result, little is known about how materials and components behave when subjected to impact loading. Some examples of sudden impact loading are vehicle impacts, crane accidents, explosions, and missile impacts. For scientists and engineers, the behavior of structural elements under various loads is a crucial topic of interest. The three basic categories of loads are constant, static, and dynamic. In contrast, impact loading caused by static or dynamic loads has not been investigated much in the past, therefore it is necessary to examine the behavior of impact loading while designing RC members [15–20]. On the other hand, investigating the behavior of dynamic impact loadings in reinforced concrete material is challenging due to the complex method and analysis technique, hence it is neglected among researchers [21–23]. However, ASTM E-23 has paid significant attention to improvements and the efficiency of impact loading determination techniques has been improved [24].

Impact load experimental investigation has been divided into two areas: specimen design for the impact load application and the utilization of testing equipment such as dropping a heavy mass from different heights. Few studies have shown interest in impact loading, especially primarily on the slabs under the impact loadings. Over the past few years, the performance of impact loading has been improved by applying numerical simulation analysis and using modern equipment to determine the behavior of dynamic load impacts in reinforced concrete slabs. Numerical simulations play a significant role in solving modern-day scientific and complex engineering problems, reducing the cost of the experiments, and increasing experiment efficiency. Hence, several studies have been conducted using numerical simulation approaches to investigate the behavior of dynamic impact loading on reinforced concrete structures. Thus, this study aimed to provide an up-to-date overview of the responses and failure behavior of slabs subjected to impact loads and researchers' trials to strengthen the slabs against impact loading. There are several important reasons to study the effect of impact loading on structures. For example, impact loading can lead to sudden and catastrophic failures of structures, resulting in loss of life and property damage. Therefore, it is critical to understand the behavior of structures subjected to impact loading to ensure their safety and to prevent potential disasters. Understanding the impact loading effect is essential in designing and constructing structures susceptible to such loads, such as buildings, bridges, and infrastructures. In addition, the theoretical background of impact loading behavior is comprehensively explained in Section 2.

2. RC Slab Behaviors under Impact Loads

Impact loads are severely intense in nature and could occur within nanoseconds as the result of collisions, explosions, falling heavy objects, earthquakes, or wave effects on offshore structures [1–3,5–8,11,12,21,24–28]. Structural responses to impact loads are categorized into three sections: (i) impulsive loading, where the impact duration ends before the structure reaches its maximum response; (ii) dynamic loading, where the structure reaches its maximum response almost simultaneously with the end of the impact duration; (iii) quasi-static loading, where the structure reaches its maximum response before the end of the impact duration. As a result, under intense impact stresses, structural components may behave in many ways [28]. An RC structure can behave in several ways when subjected to an impact load, including local and global reactions.

The impact behavior of a concrete structure failure depends on the applied force and load ratio (td/T) to the vibration period in the structure. If this ratio (td/T) is very small, the structural response is primarily governed by stress wave propagation and inertia resistance plays an essential role in resisting the impact load. On the other hand, when the ratio (td/T) is large, the structural response is a quasi-static mode and is associated with stiffness [29,30]. The impact load behavior is further classified as hard and soft. For example, when assuming that the strike is harder for stress wave propagation in a brief period, a combination of failures occur within the concrete slab. On the other hand, with a soft striking impact, energy dissipates and resists the deformation of an object. Therefore, a hard impact causes more structural damage than a soft impact. Most impact research focuses on hard impact.

The velocity of the striking object is among one of the key parameters that determines the impact behavior in the concrete element [30]. Therefore, these velocity ranges are also used to categorize low velocity (1–10 m/s), medium velocity (10–100 m/s), and high velocity (100–1000 m/s) and are required for measuring during the impact load testing period. Before the twenty-first century, most impact research focused on high-velocity impact loads; many of these studies were conducted to examine the impact response of structures to airplanes or missiles [31]. However, low-velocity impacts have recently drawn more attention. In addition to local performance, low-velocity effects may have a significant global impact on structures [32,33]. For example, dynamic impact loads produce significantly high strain rates (10^0/s–10^3/s) compared with generally static loads, which create a low strain rate of 10^{-6}/s–10^{-5}/s. Earthquakes have moderate strain rates (10^{-3} /s to 10^0 /s) and high strain rates (10^0 /s to 10^3 /s) due to blast loadings. In general, for impact and explosive problems, the inertial force is significant and the strain rate affects the constitutive properties of the concrete and the reinforcement [34].

The present design codes provide several simplified methods for predicting how RC structures will react to impact loads; however, they are unable to capture concrete structures' brittle damage characteristics under high-rate and impulsive impacts. Under high-rate impact loads, concrete structures may have localized failure modes and damages, including brittle spalling, scabbing, perforation, and punching shear failure [35], as shown in Figure 1.

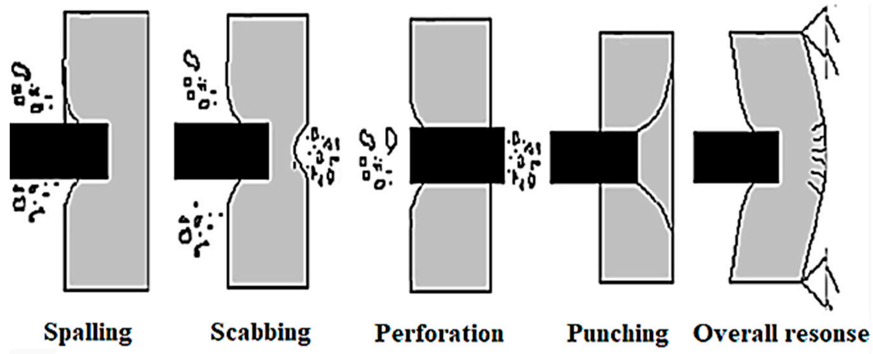


Figure 1. Failure mode under different impact loads [35].

A study by [35] summarized the design codes for different impact load behaviors proposed by different researchers/institutes and estimated the response of a concrete structure subjected to heavy loads, e.g., AASHTO [36–38] estimated vessel and vehicle collisions based on the static load and the deformation load; the Japan Society of Civil Engineers, Japan [39] estimated rock fall on the concrete object based on the performance design and impact load and absorbed energy; AS 1170.1 [40] estimated vehicle collision based on the kinetic energy of vehicles with masses between the ranges of 1500 and 2000 kg; vehicle collision by CEN [37] considered impact velocity, impact angle, deformation behavior, mass distribution, vehicle collision, and nominal load applied on the horizontal pier. However, these recommendations did not consider the dynamic strengthening effects, such as inertial and strain rate effects. Regarding the fundamental introduction and behavior of the impact load failure, this study aimed to comprehensively review slabs and plates subjected to impact loads with low velocity. In addition, the theoretical background, current design guidelines, and existing approaches for analyzing structures under impact loadings were reviewed.

3. Slab Failure under Impact Load

Slabs behave differently under dynamic impact loading because dynamic loading properties are different than static and are influenced by load strain rate. However, slab failure behavior is influenced by inertia and stress forces. Typically, the thickness of the slab is thinner and considered more vulnerable to impact loading; as a result, flexural or punching shear failures could occur [41–44]. Miyamoto et al. [45] proposed slab failure under impact load, as shown in Figure 2. The study demonstrated that slab failure behavior under increasing impact loads changed from flexural punching to punching shear.

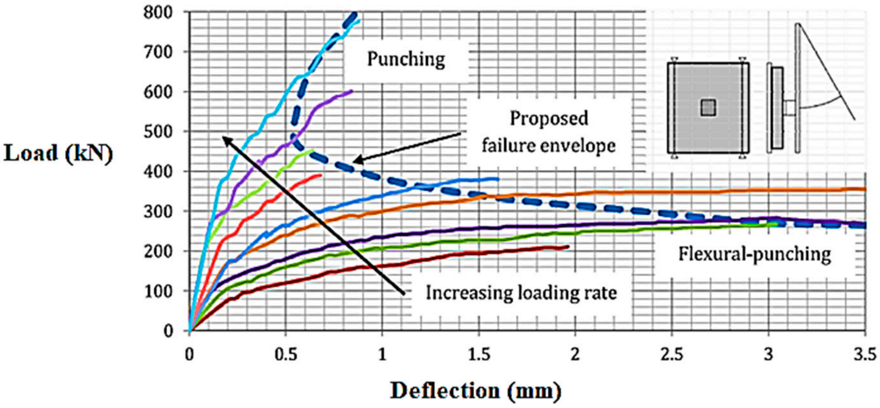


Figure 2. Load deflection response and failure mode [45].

Delhomme et al. [46] proposed a two-stage contact and post-contact phase model to predict the flexural response of the slab during and after the impact load. The study demonstrated that energy was transmitted to the slab in the contact phase and that the post-contact phase slab experienced free vibration; however, most of the parameters were not considered in this model. Sawan and Abdel-Rohman [47] proposed several analytical models to determine the dynamic response of the slab subjected to impact loadings. According to [48], the impactor velocity could determine the damage failure in the slab structure. According to [30], the impactor struck the concrete slab at low velocity, significantly causing damage. With low-velocity impactors, a slight penetration occurred in the slab; however, spalling failure occurred on the high-velocity concrete ejected from the upper layer, as shown previously in Figure 1.

The two most common failure modes caused by the elastic–plastic response were the flexural and punching shear failure modes. The RC slab bent strongly during the flexural failure mode due to extreme tension and failure due to excessive shear stress was caused by the punching shear failure of the RC slab [49]. RC slab failure under impact loading is schematically drawn in Figure 3. RC concrete experienced rapid changes under the stress and strain conditions because of the brittle concrete properties; the top surface of the RC concrete slabs was under compaction and the lower surface was under tensile force. In such cases, the strain rate increased ductility behavior and material flow stress [48,50–52].

Design parameters such as slab thickness, reinforcement percentage, concrete strength, and impact loading velocity could modify the damage of the component that was subjected to the impact load [6,7]. RC slabs under an impact load could withstand a high impact based on the design parameters of greater thickness, reinforcement ratio, concrete compressive strength, and impactor velocity [52,53]. RC slabs with a small reinforcement ratio subjected to high velocity caused local damage because the load-carrying capacity was reduced by the reduction of the reinforcement ratio in the RC slab [51].

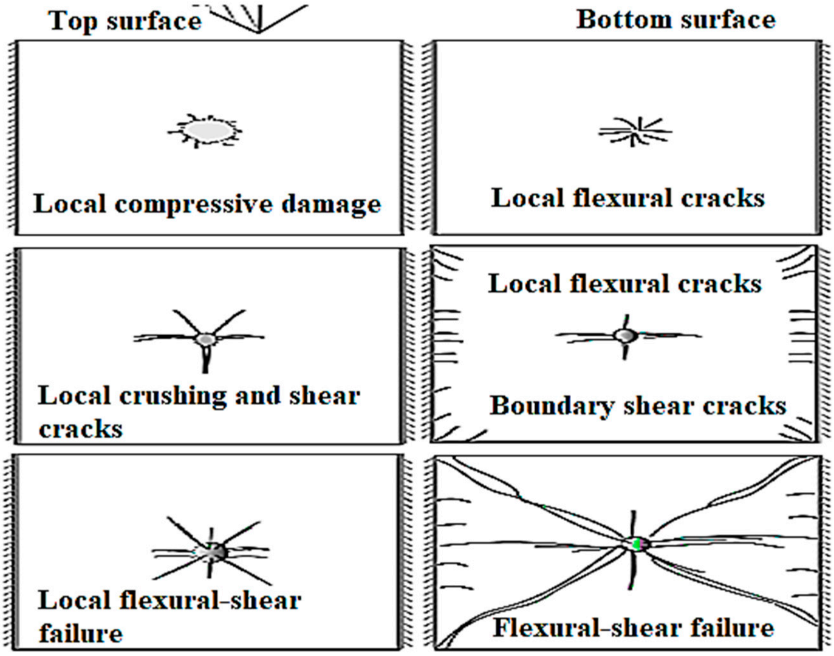


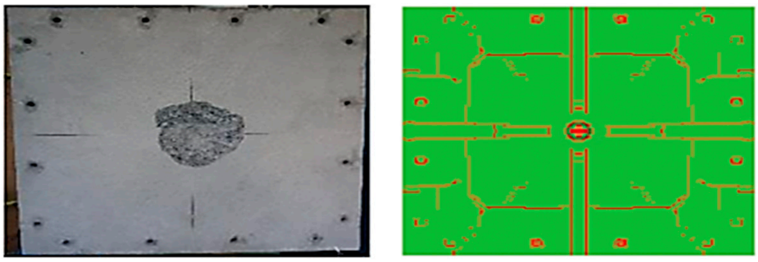
Figure 3. Under impact load, RC slab failure behavior [51].

Referring to Figure 1, an RC structure subjected to the impact load failure mode can be classified as:

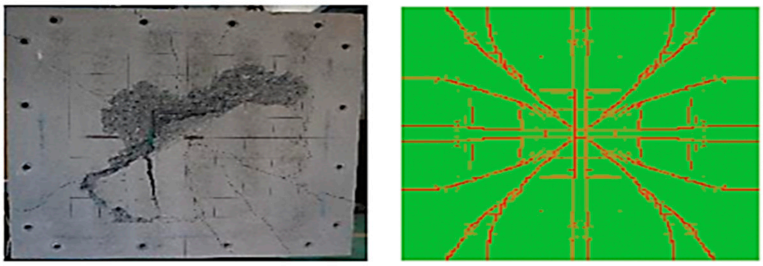
- Spalling: impactor strike and penetration with spalling on the concrete surface caused local damage or failure.
- Scabbing: the impactor strikes the RC structure and penetration surpasses the spalling, resulting in concrete scabbing from the behind/or back surface.
- Perforation: in this mode of failure, the impactor perforates the RC structure and leaves it through the back face with residual velocity.
- Punching: this failure mode occurs around the impactor load intensity area in the RC structure; local shear failure will mostly occur closer to the impact area.
- Overall structural responses: complete structure failure by shear, flexural, and bending failure occurring in the RC structure.

An RC slab subjected to higher mass/weight led to shear failure [51]. Additionally, punching shear failure spread from the upper surface to the lower surface of the RC slab. However, impact weight with high velocity produced flexural failure, leading to global failure in the concrete structure, as shown in Figure 3. Ref. [52] found that an increase in the reinforced concrete slab along with the streel ratio increased resistance against a dynamic impact load failure mode.

Ref. [54] investigated the failure modes of RC slabs subjected to a moderate impact velocity of 80-90 m/s. The result revealed that scabbing cracks on the back of the slab surface appeared as the velocity increased. Figure 4 shows the scabbing mode failure in the RC slab compared with the numerical study of [54] impact surface generated radial cracks, while the back surface showed diagonal cracks. The study concluded that, as velocity increased, the failure mode of the RC slab developed from spalling to scabbing.



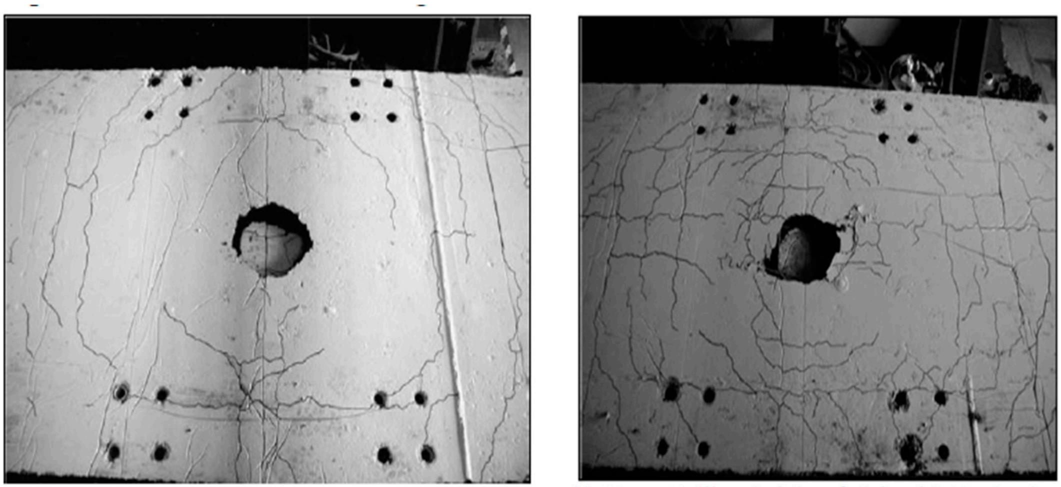
Impact surface



Back surface

Figure 4. Failure of the RC Slab (89.7 m/s moderate velocity) [54].

The RC slab failure mode depended on the reinforcement ratio and height of the impactor load; by increasing mass and height, there was a higher tendency for local failure in the RC slab [44–46,49,55–57]. At high loading rates, flexural behavior was scarcely visible [51]. The equal amount of steel reinforcement but different impact drop heights had a different impact on the RC slab failure, as shown in Figure 5. Switching to a component with increased thickness, concrete strength, and reinforcement ratio reduced the scabbing and flexural damage.



(**a**) (**b**)

Figure 5. Failure mode of RC slab. (**a**) 30 cm drop height RC slab; (**b**) 61 cm drop height RC slab [58].

The authors of [59] investigated the steel ratio effect on the RC slab failure mode. The results showed that increasing the steel ratio increased the stiffness, however it affected the impact energy less. Slabs with a higher steel ratio had less punching failure behavior [59] and protected the concrete slab from scabbing failure mode. Figure 6 shows three RC slabs with various reinforcement ratios that showed an extensive failure at the impact zone for all the cases and a scabbing failure mode on the bottom of the RC slab.

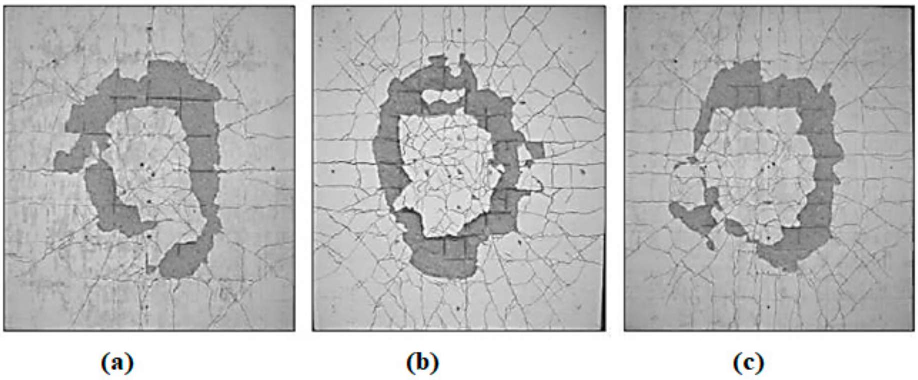


Figure 6. RC slab failure pattern for different steel ratios (**a**) steel ratio 0.273%, (**b**) steel ratio 0.42%, and (**c**) steel ratio 0.592% [59].

Study [60] conducted an experimental and numerical study to investigate the dynamic response of the RC two-way slab (1000 × 1000 × 80 mm) subjected to low-velocity impact, varying drop height, and different reinforcement ratios. The study revealed that increasing the reinforcement ratio in two-way RC slabs increased bending strength, stiffness, and toughness and considerably reduced displacement. Hence, the RC slab impact resistance increased by increasing the steel ratio. On the other hand, increasing the drop height significantly increased the damage to the RC slab. Ref. [61] used a polypropylene fiber to investigate RC slab subjected to impact load with different thicknesses and subjected to different drop heights. Polypropylene fibers (PF) by volume (0.3–1.2%) effect are shown in Figure 7, indicating that increasing the PF (%) quantity in the mix increased the impact resistance; in other words, it decreased the flexural failure of the RC slab. PF increased the impact resistance of the RC slab and decreased the punching shear failure damage of the structure.

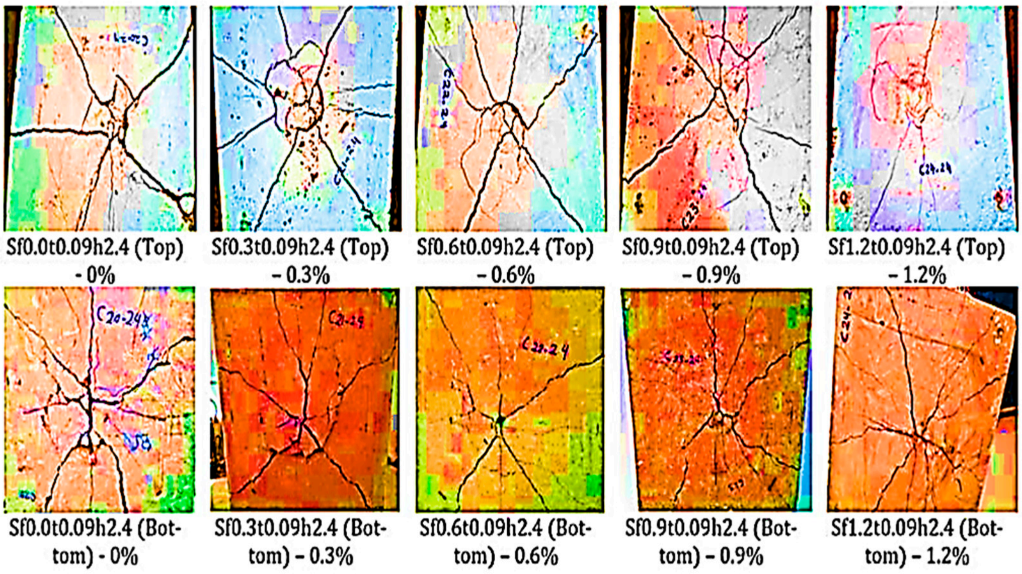
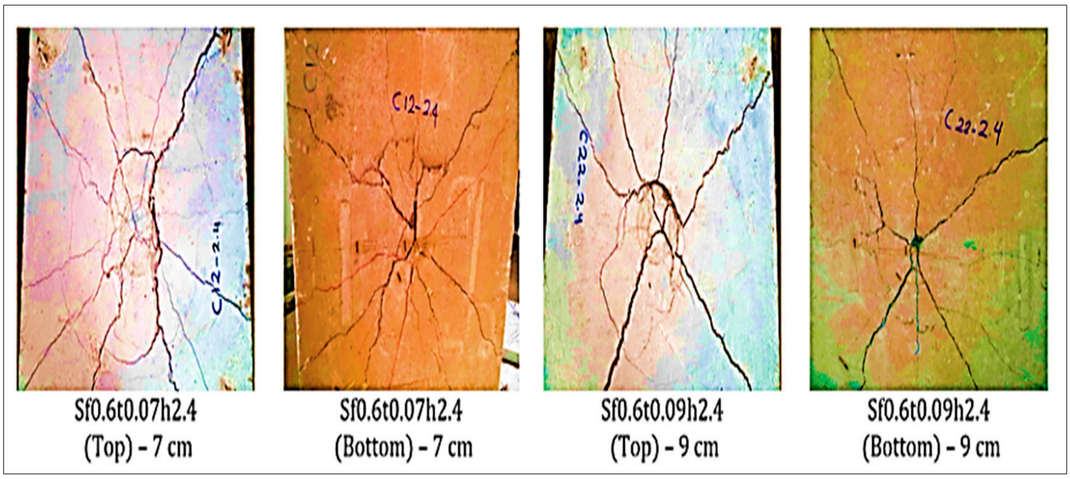


Figure 7. Polypropylene fiber (volume %) effect on RC slab subjected to impact load [61].

Figure 8 revealed that RC slab thickness significantly affected the flexural and punching shear failure, as the thickness increased by 28% and the punching shear failure damage decreased by 35% [61].



Sf0.6t0.07h2.4 (Top) - 7 cm

Sf0.6t0.07h2.4 (Bottom) - 7 cm

Sf0.6t0.09h2.4 (Top) - 9 cm

Sf0.6t0.09h2.4 (Bottom) - 9 cm

Figure 8. RC slab thickness effect (7–9 cm) [61].

4. Normal RC Slabs Subjected to the Impact Load

The slab is the most used structural component and is frequently employed with load-bearing beams. The emotional reactions and failure behaviors of concrete slabs and plates under different velocities were studied under low [59,62–64], moderate [43], and high [53]. Dynamic impact loads subjected to slabs have been extensively studied in the literature, using analytical [23,53,65], numerical [23,43,65,66], and experimental [14,63,67,68] methods. Typically, the two most common failure mechanisms in concrete slabs were localized failure and punching shear failure at high-impact loads [14] and projectile loads [23,53,65–68] at low-impact loads (globally dispersed fracture patterns in slabs).

The concrete structure could be subjected to several impact loads based on the impact load behavior. Previous studies performed low/moderate and high-velocity impact testing to investigate the behavior of the concrete structure.

Although many researchers have investigated the impact load and structural response and failure behaviors in RC beams and columns, this study mainly focused on RC slabs. Sawan and Abdel-Rohman [47] performed a low-velocity impact test on a slab by repeatedly dropping a steel ball onto the (750 × 750 × 50) mm reinforced concrete slab from increasing drop heights. Findings from the study [47] indicated that as the drop height increased the maximum deflection of the slab also increased, however the increase in the reinforcement ratio enabled a decrease in the deflections, as shown in Figure 9. The slab subjected to the impact loads is summarized in Table 1.

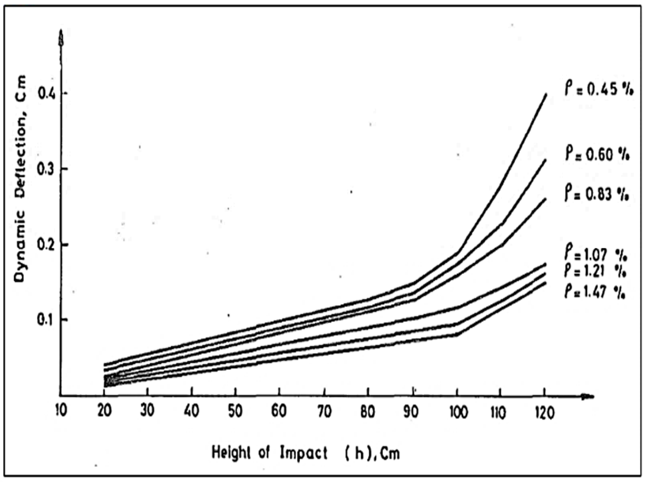


Figure 9. Influence of drop height of (h) on a maximum dynamic deflection for different values of re-enrolment ratio (ρ) [47].

Table 1. Summary of the slab-subjected impact loads.

Ref.	Approach/ Methodology	Parameters	Findings and Remarks
Sawan and Abdel-Rohman [47]	Experimental	Drop Height Steel Ratio	Deflection increased as the drop height increased. By increasing reinforcement, deflection decreased.
Mouwainea, and Said [69]	Numerical (ABAQUS)	Slab Thickness Steel Ratio	Slab Thickness increased and deflection decreased by (48–87%). Steel ratio increased by (0.58–1%) did not affect much, therefore concluded that impact force was not affected by steel ratio but by thickness.
Chen and May [42]	Experimental Parametric study	Impactor Mass Impactor Shape (hemispherical and flat plat shaped impactor)	The drop weight with a hemispherical tip caused a larger circular scab zone on the underside of the plate.
Kishi et al., [70]	Experimental	Mass of Hammer (1000, 3000, 5000 kg) Slab Thickness Steel ratio	Thickness determined the maximum impact force, with no role in the ratio and arrangement of reinforcement. Flexural cracking and eventual punching shear failure were observed in all tests.
Zineddin and Krauthammer [14]	Experimental	Reinforcement Ratio Drop Heights (152, 305, and 610 mm)	Slabs under impact failed due to punching shear, with little bending involved. When drop height increased, impact behaviour on the slab dominated, resulting in punching or direct shear increase. Less steel reinforcement induced a brittle failure in concrete; therefore the steel ratio was considered an influential parameter.
Batarlar [30]	Experimental	Type of Loading (impact and static) Steel Ratio Steel Spacing 210 and 320 kg mass Fixed Drop Height 2500 mm	An increasing proportion of longitudinal reinforcement affected the ductility and static load capacity. Moreover, the specimen with the highest reinforcement ratio sustained the highest load. The impact behaviour was significantly different compared with the static behaviour. The load-carrying mechanisms and distribution of the forces in the specimens were highly affected due to the inertia forces caused by accelerations resulting from the impact.

Table 1. *Cont.*

Ref.	Approach/ Methodology	Parameters	Findings and Remarks
Jeddawi [71]	Experimental	Type of Loading (impact and static) Fixed Mass Weight 475 kg Fixed Drop Height 4.15 m Fixed Impact Velocity 9 m/s Fixed Steel Ratio 1.0%	The energy absorption of the impact load was about 1.4 times the static load. The most considerable value of deflection was slightly higher for the impact loading. The specimen failed in localized punching mode under dynamic load, while the specimen failed in ductile punching mode under static load. Furthermore, the same specimen configuration with high-strength concrete was tested under the same dynamic load; the test revealed that the slab failed in ductile punching mode.
Yılmaz et al., [72]	Experimental and Numerical (ABAQUS software)	Fixed Hammer Mass 84 kg Drop Heights (1000, 1250, 1500 mm) Steel Ratio CFRP Arrangement	The bending strength, toughness, and stiffness were increased by increasing the steel ratio of two-way RC slabs. CFRP (carbon fiber reinforced polymer) strengthening technique significantly improved the impact behaviour of the RC slab for low-velocity load.
Said and Mouwainea [73]	Experimental	Fixed Drop Height 1.5 m Fixed Impactor Mass 50 kg Fixed Slab Thickness Fixed Velocity 5.8 m/s CFRP Arrangement	The increase in the area of the CFRP layer under the impact region led to a greater deflection decrease. Concerning acceleration, it was evident that the distribution of forces acting on the plate also varied throughout the event. The evolution of the inertial force resulted in load distributions significantly different from those developed in static test conditions. The evolution of inertial forces in impact loading conditions resulted in observed responses and failure patterns governed by shear. Strengthening method significantly improved the impact behaviour of the slab and led to maximum impact resistance.
Anil et al., [63]	Experimental and Numerical (ANSYS Explicit STR)	Support Layout Support Type (Fixed and Hinge) Fixed 5.25 kg Hammer. Fixed Drop Height 500mm	The performance of RC slabs was significantly affected by the sort and arrangement of their supports. Decreased acceleration was observed as specimen support rigidity was increased. The support structure’s design impacted the maximum allowable acceleration, velocity, and displacement. Maximum accelerations decreased as the amount of impact drops increased. Acceleration values computed numerically were more significant than those measured experimentally.

Table 1. *Cont.*

Ref.	Approach/ Methodology	Parameters	Findings and Remarks
Kühn and Curbach [49]	Experimental	Drop Height Velocity Impactor Mass Impactor Size Impactor Shape	As the height increased, velocity of the impactor also increased. The height of the drop, velocity, and mass significantly affected the impact behaviour. However, shape and mass effects were hard to understand.
Anas et al., [56]	Numerical (ABAQUS)	Steel Orientation (3 layers flexural tension steel) Drop Height 2500 mm Impactor Mass 105 kg Velocity 7 m/s	Slabs with three layers of flexural tension steel performed better in less displacement and control damage than two layers of steel.
Şengel et al., [13]	Experimental Numerical (Ls-Dyna)	Impactor Geometry (hemispherical) Flat (with different surface area hammer) Impact Area Impactor Mass Impactor Velocity (refer to Figure 3)	Increasing the impact area between the impactor and RC slab caused maximum impact. Hemispherical caused less impact and flat impactor with the maximum square area (150 × 150) caused the highest impact. Maximum acceleration, displacement, and high energy absorption caused by increasing impact mass/weight and velocity.
Mizushima and Iino [74]	Experimental Numerical (LS-Dyna)	Thin Slab Low Velocity (17.9 m/s) Drop Height (16 m)	Increasing the amount of reinforcement led to increased perforation resistance.

Several techniques have been used to increase RC slab punching shear capacities, such as bent-up bars, close stirrups, shear studs, and the utilization of high-strength concrete [61]. As summarized in Table 1, the behavior of RC slabs under impact loads was investigated experimentally, numerically, and analytically by several researchers. Table 1 shows that effective parameters such as drop height, steel ratio, slab thickness, support layout and support types, impactor velocity, impactor geometry, and impactor mass were some parameters used in past studies [14,30,42,47,49,69–73]. Studies indicated that slab failure was two-way punching shearing, slab thickness resisted impact load, high steel ratio effectively prevented spalling of concrete, and punching shear resistance was twice higher under static impact loading. Anas et al. [55,75] studied the orientation of steel and strengthening RC slab with C-FRP; these techniques showed better performance and resistance to impact loading. Said and Mouwainea [76] conducted a series of experimental tests to investigate RC slab high-mass and low-velocity impact behavior by increasing the steel ratio. The study found that, by increasing steel ratio and compressive strength, the penetration depth decreased, impact resistance increased, and displacement value decreased.

5. High-Strength RC Slab Subjected to Impact Load

In contrast, the second group of studies considered high-performance concrete or materials' effects on the behavior of the slab under impact loads. The two most common types of failure occurring in concrete slabs under low-velocity impact loads were globally distributed crack patterns [64,67] and a localized and punching shear failure under high-velocity impact loads [68,77]. For brittle failure and improving the shear and flexural resistance of concrete structures against impact load, climate effect, and extreme loads, the utilization of high-strength composite materials has been introduced. As a result, the performance of the concrete has significantly improved. Therefore, several researchers have focused on high-strength concrete slabs by the addition of composite materials and concrete performance has been investigated, such as steel fibers [59], CFRP [72,73], FRP [78], ultra-high-performance concrete (UHPC) [62], and hybrid bamboo fiber (HBF) [41]. Table 2 reviews and summarizes high-performance concrete and impact loads.

Table 2. Summary of high-performance slabs subjected to impact loads.

Ref.	Approach/ Methodology	Materials/ Types of Concrete	Parameters	Findings and Remarks
Hummeltenberg et al., [79]	Experimental	PC (Plain Concrete) HPC (High-Performance Concrete) UHPC (Ultra-High-Performance Concrete) UHPFRC (Ultra-High-Performance Fiber-Reinforced Concrete)	Drop Height (3-9m) Velocity (7.7-13.3 m/s)	Compared with the standard concrete, HPC and UHPC showed better results by increasing the resistance of the slab against the impact load.
Wang and Chouw [41]	Experimental and Theoretical Analysis	FFRP (Flax Fiber Reinforced Polymer) CFRC (Coconut Fiber Reinforced Concrete) PC (Plain Concrete)	Strain Energy Absorption Drop Height	FFRP-CFRC absorbed more energy than CFRC and PC. Strain energy absorption increased by increasing drop height. CFRC absorbed 135% more strain energy than PC.
Hrynyk and Vecchio [59]	Experimental	SFRC (Steel Fiber Reinforced Concrete) PC	Impactor Weight (150-180-210-240-270-300 kg) Steel Ratio Under Low Velocity	SFRC showed better performance than PC. The addition of SFRC effectively increased slab capacity, reduced crack widths and spacings, and mitigated local damage under impact.
Verma et al., [62]	Experimental, Numerical (Abaqus), and Analytical	UHPC PC	Slab Thickness (10 and 15 mm) Under Low Impact Velocity Impactor Energy Fiber Contents	Fiber-mix slabs performed bridging action and increased the cracking resistance. Slabs with greater thickness offered more resistance to the impact loads.
Yoo et al., [80]	Experimental	NSHSDC (No-Slump, High-Strength, High-Ductility Concrete) FRP PC	Maximum Displacement Energy Dissipation Capacity	NSHSDC showed excellent impact resistance and high strength and had the lowest deflections. The energy dissipation capacity of reinforced concrete slab strengthened with NSHSDC was higher than FRP and PC.
Rao et al., [81]	Experimental	SIFCON (Slurry Infiltrated Fiber Concrete) FRC PC	Fiber Volume	The energy-absorption capacity of SIFCON slabs increased with the increase in fiber volume.

Table 2. *Cont.*

Ref.	Approach/ Methodology	Materials/ Types of Concrete	Parameters	Findings and Remarks
Sadraie et al., [82]	Experimental and Numerical (LS-DYNA)	GFRP (Glass Fiber Reinforced Polymer)	Steel Ratio Steel Arrangement Thickness	GFRP slabs provided slightly less resistance than reinforcement. Increasing the reinforcement ratio decreased displacement. Greater slab thickness enhanced performance, leading to reduced displacement and cracks. Steel arrangement significantly enhanced the performance.
Batarlar et al., [44]	Experimental	Carbon Textile Reinforcement	Velocity of Loading	Increasing striker velocity created significant damage and failure occurred on high strike velocity. Carbon textile reinforcements were very effective in enhancing impact capacity.
Anas et al., [55]	Numerical (ABAQUS)	C-FRP Laminate C-FRP Strip PC	Impactor Mass 105 kg Drop Height 2500 mm Impacting Velocity 7 m/s	Slab strengthening with steel sheet/C-FRP laminate and C-FRP strips showed incredible resistance to impact loads and prevented slab failure.
Batarlar and Saatci [57]	Numerical (LS-DYNA)	CFTR (Carbon Fiber Textile Reinforcement)	Slab Thickness Impactor Mass and Size Velocity Steel Ratio CFTR Ratio	CFTR showed better performance and lower displacement. Slab thickness contributed to resistance to the impact load. Steel and CFTR ratio did not show a dominating effect.
Jin et al., [50]	Numerical (ABAQUS)	GFRP	Impactor Mass Impactor Velocities (1.98 -13.280)	The peak impact load increased by 500% when the impact velocity changed from 1.98 to 13.28. Impactor weight increased the failure or damage in the RC structure. Various studies have verified that increasing impactor mass significantly impacts the RC slab behavior.

RC slabs subjected to impact loadings can behave differently compared with those structures under static loads. Dynamic impact loading patterns are also different from static loading. Jin et al. [50] drew links between various impact velocity ranges (1.98 m/s to 13.28 m/s), as shown in Figure 10a, b. It was found that the peak impact force, impact force plateau value, and impact duration increased almost linearly with the increase in impact velocity. In other words, the peak impact load increased by 500% when the impact velocity changed from 1.98 to 13.28. The impact velocity was among the significant contributing parameters that damaged the RC structures/slab behavior under impact load; by increasing the impact velocity, the impact damage increased [14,19,25,30,41,42,44–51,55,57,63,69–71,74–84]. In conjunction with the impactor velocity, the impact mass has been studied in the literature and it has been revealed that, when the impactor weight increased, the failure or damage in the RC structure grew. Various studies have verified that increasing the impactor mass significantly impacted the RC slab behavior.

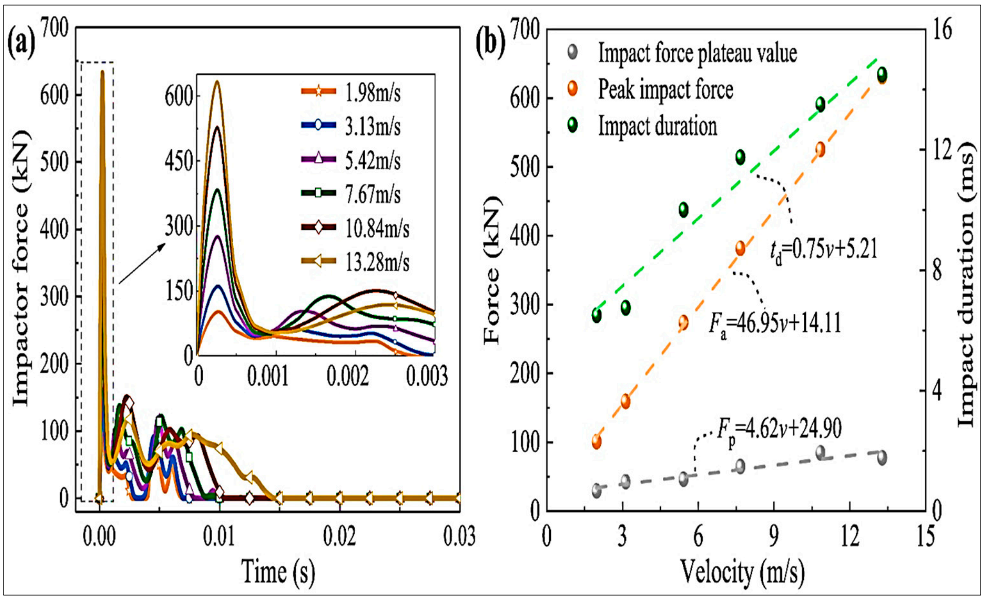


Figure 10. Effect of impact velocity on the impact forces of slabs reinforced by GFRP bars. (**a**) Time history of impact force; and (**b**) Maximum impact force, impact force plateau value and impact duration [50].

6. Discussion

This paper aimed to review reinforced concrete slabs subjected to impact loading systematically. Although the accidental collision or effect of the dynamic impact loading in concrete structures rarely occurs, it could be catastrophic [19]. The concrete slabs are subjected to local damage because of the impact loads. This study categorized the parameters causing the impact damage to the RC slab. RC slab behavior subjected to the impact loading was discussed in the above section, followed by the failure modes of standard reinforced concrete versus high-strength reinforced concrete subjected to the impact load, which has been comprehensively discussed in this paper.

Impact loads are severely intense and could occur within nanoseconds due to collisions, explosions, falling heavy objects, and earthquakes or waves affecting offshore structures [1–3,5–7,11,12,21,23–25,27,28,81]. Structural responses to the impact load are categorized into impulsive, dynamic, and quasi-static loading. Under intense impact stresses, structural components may behave in many ways [28]. An RC structure can behave in several ways when subjected to the impact load, such as the local and global reactions of the impact load [18,30]. The impact behavior of concrete structure failure depends on the applied force and load ratio (td/T) to the vibration period in the structure [24,27–32]. Zhang et al. [35] summarized the design code and RC structure behavior to the subjected loads based on the nature of the impactor collision and subjected RC structure response to the impact loads.

Slab failure behavior is influenced by inertia and stress forces [67]. Typically, the thickness of the slab is thinner and considered more vulnerable to impact loading due to flexural or punching shear failures [41,42,44,53,57,67,77]. Miyamoto et al. [45] proposed slab failure under the impact load, demonstrating that slab failure behavior under increasing impact loads changes from the flexural punching shear failure. Delhomme et al. [46] proposed a two-stage contact and post-contact phase model to predict the flexural response of the slab during and after the impact load. Sawan and Abdel-Rohman [47] proposed several analytical models to determine the dynamic response of the slab subjected to the impact loadings. An RC slab under impact load can withstand high impact based on the design parameters of increased thickness, reinforcement ratio, concrete compressive strength, and impactor velocity [52,53]. RC slabs with a small reinforcement ratio subjected to high velocity cause local damage, because the load-carrying capacity is reduced by the reduction of the reinforcement ratio in the RC slab [51]. Design parameters, such as slab thickness, reinforcement percentage, concrete strength, and impact loading velocity, can modify the damage of the component subjected to the impact load [6,7]. The two most common failure mechanisms in concrete slabs are localized failure and punching shear failure at high-impact loads [14] and projectile loads [23,53,65–68] at low-impact loads, producing globally dispersed fracture patterns in slabs.

An RC slab subjected to a higher mass/weight leads to shear failure [83]. Kataoka et al. [54] investigated the failure modes of RC slabs subjected to a moderate impact velocity of 80–90 m/s. They revealed that a scabbing crack on the back of the slab surface appears as the velocity increases. Hrynyk and Vecchio [59] investigated the steel ratio effect on the RC slab failure mode; the results revealed that increasing the steel ratio increases the stiffness but has less effect on the impact energy. Therefore, slabs having a higher steel ratio have less punching failure behavior [59] and protect the concrete slab from the scabbing failure mode. Yilmaz et al. [60] revealed that, by increasing the reinforcement ratio in two ways, RC slabs increase bending strength, stiffness, and toughness and considerably reduce displacement; hence, RC slab impact resistance is increased by increasing the steel ratio.

On the other hand, increasing the drop height significantly increases the damage to the RC slab. Al-Rousan [61] found that increasing the mix's PF (%) quantity increases the impact resistance and decreases the RC slab's flexural failure. PF (polymer fiber) increases the impact resistance of the RC Slab and decreases the punching shear failure damage of the structure. Several techniques have been used to increase the shear punching capacity of an RC slab, e.g., bent-up bars, close stirrups, shear studs, and the utilization of high-strength concrete [61].

Table 1 summarizes the studies conducted experimentally, analytically, and numerically to investigate the operational parameters of plain reinforced concrete slab subjected to impact loads such as drop height, steel ratio, slab thickness, support layout and support types, impactor velocity, impactor geometry, and impactor mass used in past studies [14,30,42,47,51,52,63,69–72,82–84]. Slab thickness, impact load, and high steel ratio prevent concrete spalling, and punching shear resistance is twice as high under static impact loading. Anas et al. [55,75] revealed that the orientation of the steel and the strengthening of the RC slab with CFRP show better performance and resistance to impact loading. Said and Mouwainea [76] conducted experimental tests to investigate the high mass and low-velocity impact behavior in RC slabs by increasing the steel ratio. The study found that with increasing steel ratio and compressive strength, the penetration depth decreases, the impact resistance increases, and the displacement value decreases.

Table 2 summarizes the previous studies on high-performance or high-strength concrete reinforced concrete slabs subjected to impact loads. The brittle failure and improvement in the shear and flexural resistance of concrete structures against impact load, climate effect, and extreme loads and the utilization of high-strength composite materials have been introduced. As a result, the performance of the concrete has significantly improved. Therefore, several researchers have focused on a high-strength reinforced concrete slab with the addition of composite materials and concrete performance has been investigated, e.g., steel fibers [59], CFRP [51,72], FRP [78], ultra-high-performance concrete (UHPC) [62], and hybrid bamboo fiber (HBF) [41]. These studies reveal that the addition of high-strength materials significantly improves the compressive and flexural strength of the reinforced concrete slab and increases impact resistance. However, other working parameters, such as high velocity, impact mass, materials properties, slab thickness, steel arrangement, and steel ratio, are among the factors explaining why the subjected slab behaves differently according to the condition.

7. Conclusions and Recommendations

The systematic literature review was established to better understand RC slab behavior when subjected to the dynamic impact load. The study division was based on past investigation into two major groups of regular concrete slabs subjected to impact loading and high-strength reinforced concrete slab subjected to the impact load, where working parameters were considered the same in both cases, such as velocity, slab thickness, steel ratio impactor weight, drop height, etc. This review was limited to the RC slab that was subjected to low-impact velocity; other structural members, such as beams and column or piers, were not reviewed or discussed in this paper. This paper drew few significant conclusions based on the past studies' findings.

RC slabs are rarely subjected to impact loads. However, they behave differently under dynamic impact loading and, generally, RC slabs experience local and global failure modes. Slab failure behavior is influenced by inertia and stress forces.

Dynamic impact loads produce significantly high strain rates (10^0/s–10^3/s) compared with the generally low static load-producing strain rate of (10^{-6}–10^{-5} s^{-1}). Earthquakes produce moderate strain rates (10^{-3} /s to 10^0 /s) and high strain rates (10^0 /s to 10^3 /s) by blast loadings.

The intensity of impactor velocity plays a crucial role in the RC slab failure mode. Low/moderate and high velocities have different impacts and damage increases by increasing the impactor's velocity.

Impactor weight significantly affects the RC slab subjected to impact load; as the mass/weight increases, the failure mode changes severalty or damage depending on the impactor mass.

The impactor drop height is among the critical working parameters. As the drop height increases, the damage failure in the RC slab becomes more vulnerable; constant drop heights with different impact velocities and mass have shown different results. However, this paper review showed that impactor drop heights must be addressed and considered as one of the main working parameters.

In both cases, standard concrete slabs or high-strength concrete slabs with different thicknesses show different results. However, this study can conclude that increasing the thickness of the RC slab offers higher resistance to the impact load compared with the less thick slab.

The steel ratio or the reinforcement ratio significantly influences the RC slab subjected to the impact loading; as the reinforcement ratio increases, the impact resistance increases. Moreover, the steel pattern or arrangement differs from the impact loads.

Impactor geometry (size and shape) flat/hemispherical with different surface areas, increasing the surface area between the impactor and the RC slab causes maximum impact. A hemispherical impactor causes less impact than a flat impactor with the maximum square area.

Replacement and addition of the high-performance or high-strength RC slab shows significantly positive and high impact resistance (refer to table summarizing various researchers attempts to use different materials to enhance the compressive and flexural properties of concrete), resulting in higher impact resistance.

Past studies have revealed that UHPC, HPC, UHPFRC, CFRC, SFRC, NSHSDC, FRP, SIFCON, GFRP, and CFTR show better performance and provide high-impact resistance; however, this is strictly conditional on the mix-design ratio and on working parameters.

8. Limitations and Future Studies Recommendations

This study focused on a specific type of slab configuration (e.g., flat slab, one-way slab) and may not have captured the behavior of other slab types. Simplifications in the modeling approach may have affected the accuracy of the results, e.g., neglecting nonlinear material behavior or creep effects. Experimental testing was conducted at a reduced scale and scaling effects may have influenced the response of full-scale slabs. In the future, researchers could: investigate the effect of different reinforcement configurations, including different bar sizes, spacing, and detailing, on the behavior of slabs under impact loading; explore the behavior of slabs under impact loading at elevated temperatures, considering the potential influence of fire or blast scenarios; study the long-term behavior and durability of strengthened slabs under cyclic impact loading to assess the structure's service life performance.

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