Behaviour of Slabs Under Impact Loading: A Review

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Abstract

The behaviour of slabs under impact loading differs significantly from that observed under short-term or long-term static loading conditions. Such dynamic loading scenarios typically arise from vehicular collisions, explosive events, or other forms of sudden impact. This paper aims to synthesise and critically evaluate the extant literature concerning the response of slabs subjected to impact loading. The investigation encompasses an analysis of the salient factors influencing slab behaviour, elucidation of failure mechanisms, examination of methodologies for simulating impact loading, and a critical appraisal of pertinent design code recommendations. Through this comprehensive review, it has been ascertained that reinforcement configuration plays a pivotal role in augmenting the resistance of slabs to impact loading. Furthermore, the predominant mode of failure observed in such scenarios is punching shear. This finding underscores the necessity for meticulous consideration of shear capacity in the design of impact-resistant slab structures.

Keywords: Impact Load; Slabs Behaviour; Failure Mode; UHPC.

مراجعة ادبية شاملة لسلوك السقوف تحت تاثير الحمل الصدمي

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الخلاصة:

يختلف سلوك الألواح تحت تأثير الأحمال الارتطامية بشكل كبير عن السلوك الذي يتم ملاحظته في ظل ظروف التحميل الساكنة قصيرة الأمد أو طويلة الأمد. تنشأ مثل هذه السيناريوهات المتعلقة بالتحميل الديناميكي عادةً من الاصطدامات بالمركبات أو الأحداث الانفجارية أو أشكال أخرى من التأثير المفاجئ. تهدف هذه الورقة إلى تلخيص وتقييم الأدبيات الموجودة فيما يتعلق باستجابة الألواح المعرضة للحمل الارتطامي بشكل نقدي. يشمل التحقيق تحليل العوامل البارزة التي تؤثر على سلوك الألواح، وتوضيح آليات الفشل، وفحص منهجيات محاكاة الحمل الارتطامي، والتقييم النقدي لتوصيات كود التصميم ذات الصلة. من خلال هذه المراجعة الشاملة، تم التأكد من أن تكوين التعزيز يلعب دورًا محوريًا في زيادة مقاومة الألواح للحمل الارتطامي. علاوة على ذلك، فإن الوضع السائد للفشل الملحوظ في مثل هذه السيناريوهات هو القص الثاقب. يؤكد هذا الاكتشاف على ضرورة مراعاة سعة القص بدقة في تصميم هياكل الألواح المقاومة للتأثير.

1. Introduction

In the realm of structural engineering, the accurate prediction of long-term deflection in slabs is of paramount importance. This critical parameter informs the determination of requisite slab thickness, thereby ensuring compliance with essential serviceability limits. The significance of this consideration cannot be overstated, as it directly impacts the longevity and functionality of structures.
Slabs, as fundamental structural elements, are frequently subjected to impact loading from diverse sources. These dynamic forces may originate from vehicular collisions, blast events, or the impact of falling objects. The assessment of slab response under such transient loading conditions is crucial for maintaining the safety and serviceability of buildings and infrastructure [1]. This evaluation process is inherently complex, necessitating a nuanced understanding of various influential factors. The behaviour of slabs under impact loading is governed by a multitude of parameters. Primary among these are slab thickness, reinforcement configuration, material properties, foundation stiffness, and the characteristics of the applied load—both in terms of duration and magnitude [2, 3]. These factors interact in intricate ways producing complex patterns of deformation, stress distribution, and energy dissipation within the slab structure [4-6]. The boundary conditions of the slab further modulate these responses, adding another layer of complexity to the analysis. In light of these challenges, the development of robust design and retrofit strategies has become a focal point of research and practice. Such strategies may encompass the incorporation of additional reinforcement the

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utilisation of energy-absorbing materials, or the implementation of advanced damping systems. These interventions aim to enhance the impact resistance and overall resilience of slab structures [5]. Thereby mitigating the risk of catastrophic failure under extreme loading conditions. It is crucial to recognise the fundamental distinctions between impact loads and static loads. The former are characterised by their abrupt onset and short-lived nature with their effects on structures being primarily dependent on the rate of loading rather than its duration. This transient quality of impact events significantly influences the response mechanisms of structural slabs [6, 7], necessitating specialised analytical approaches and design considerations. Given the complexity and importance of this subject, this paper endeavours to present a comprehensive synthesis of published data pertaining to the behaviour of slabs subjected to impact loading. Through a rigorous examination of the extant literature, we shall elucidate the critical factors influencing slab behaviour, delineate the predominant failure mechanisms, scrutinise methodologies for simulating impact loading scenarios, and critically appraise the recommendations put forth by pertinent design codes.

2. Experimental Studies on Impact-Loaded Slabs

2.1 Test Methods and Setup

Experimental investigations used various methods to simulate real-world impact loading scenarios on slabs, including the Falling Weight Impact Test (FWIT), Drop Tower Tests (DTT), Impact Pendulum Tests (IPT), and Shock Tube Experiments (STE) [8,9]. Tests method selection was depending on the specific research aims and required accuracy in representing actual impact events. Data acquisition was employed to capture the transient slab behaviour under impact loading. Tooles such as high-speed cameras, accelerometers, strain gauges and LVDTs were typically used to quantify and record the displacement and dynamic behaviour [10,11]. Test samples and boundary condition selection was critical to ensure the accuracy in experimental studies [12]. Full-scaled or scaled models were used based on available resources and objectives. Boundary constraints i.e. simply-supported, clamped or free edges are influencing slab response under impact loads significantly [13]. Material properties were important to understand its dynamics behaviour under impact loading [14]. Experimental investigations involve material testing to determine properties such as compressive strength, tensile strength and dynamic modulus. Furthermore, meticulous control and documentation of impact parameters like drop height, impact angle and velocity were necessary to ensure reliability and reproducibility of results [15].

2.2 Response Characteristics

Studies of how slabs react when hit hard teach us a lot about their behaviour when things happened suddenly. Researchers tested slabs in various methods to study their respond. These experiments show some consistent traits of slab reactions to impacts that were worth reviewing.

In general, slabs tend to bend then break in certain ways when impacted. Mapping out the deformation patterns tells us how well a slab might stand up to a hit and where the weak points were. Stress inside the slab also shapes its reaction. Tests show strikes often create concentrated stress hot-spots near the point of impact. The specifics depend on the slab's materials, supports, and what hits it. Understanding the stress landscape was important for designs tough enough to take an impact. Studies also showed slabs absorb a lot of energy when slammed, which differs from each other depending on their boundary conditions, material proprieties and reinforcement conditions. Measuring the energy loss was key to predicting potential cumulative damage and engineering better shock absorbers to improve resilience. The ratio between a slab's peak reaction to a sudden hit versus a slow push another critical dynamic was the possible failure limit and inform the safety margins needed in impact-ready designs.

2.3 Failure Modes and Damage Assessment

Experimental investigations into slab response under impact loading provide important insights into failure modalities and damage mechanisms induced by sudden, dynamic loading. Elucidating failure modes and damage patterns was imperative for the safe, resilient design of structures subjected to impact events. This overview summarizes key findings from experimental impact loading studies regarding slab failure and damage assessments. Various failure modes manifest in slabs under impact loads, including flexural, shear, and punching shear failures (Figure 1). Flexural failure arises from excessive bending moments, leading to cracking and rupture [22]. Shear failure involves sliding along slab interfaces, while punching shear stems from concentrated loads inducing failure around supports [23]. Various methods were utilized to assess damage in experimentally tested slabs subjected to impact loading. Visual inspection and crack mapping provide initial damage detection, while strain analysis, imaging techniques, and digital image correlation (DIC) quantify crack patterns and surface strains to characterize damage distribution and intensity [25]. Structural health monitoring (SHM) techniques had emerged to continuously monitor slab condition during and after impact events. SHM technologies like embedded sensors and wireless systems deliver real-time structural response data, enabling damage detection and diagnosis. SHM was critical for evaluating post-impact integrity and remaining service life. [26, 27].

Advanced techniques including DIC and SHM were invaluable for quantifying and characterizing the extent of damage in impacted slabs. By elucidating damage progression, these technologies inform effective retrofitting and mitigation strategies. Overall, the multifaceted experimental damage assessment methodologies provide critical insights into failure modalities and fracture behaviour under impact loading.

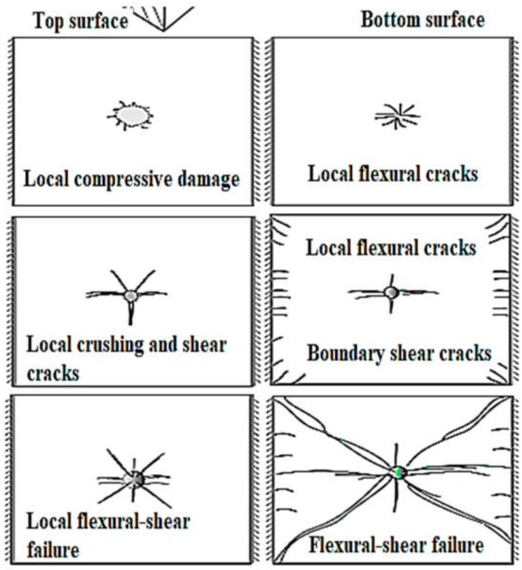

Figure (1): Failure modes of RC slab under impact load [24]

2.4 Influence of Material Properties

Experimental research showed that, mechanical proprieties might significantly influence the slab behaviour under impact loading. Concrete tensile and compressive strength showed a direct response to the slab's resistance to the impact loading. Where the higher strengths lead to the greater load resistance and energy dissipation. Nevertheless, reinforcement configurations also improve flexural and shear resistance during impact events dramatically [28-30]. Moreover, ductile materials endure substantial plastic deformation before failure and enhancing energy absorption. Were high toughness materials resist crack development, reducing the brittle failure risks under impact loads [30-31]. Material anisotropy, such as in fiber composites or orthotropic mediums, also affects slab impact response as shown through studies on directionally-dependent performance. Furthermore, material heterogeneity and variability influence structural safety under variable dynamic demands [32-34].

3. Numerical Simulations of Slab Response

Finite element analysis (FEA) was widely utilized in numerical simulations to complement experimental slab impact studies by enabling detailed investigations into dynamic response and failure. This overview summarizes FEA model applications in experimental impact research and their significance for advancing structural behaviour insights. Experimental results serve to validate FEA models by comparing simulated versus observed deformation patterns, stress states, and failure modes. [35,36] FEA enables extensive parametric studies by systematically varying material properties, reinforcements, boundary conditions, and impact characteristics to quantify their influence on response. This facilitates identifying critical design factors and optimizing slab performance under dynamic loads. [37] Simulations can pinpoint regions of concentrated stress, crack formation, and failure initiation for enhanced response characterization. [38] Analyzing simulated failure modes and damage aids in elucidating failure mechanisms to inform structural assessments and retrofitting. [39] Sensitivity analyses quantify the effects of uncertainties in material parameters, loading, and modeling assumptions on slab response. The synergistic use of simulation and experimentation significantly empowers impact-resistant and resilient structural design. Overall, FEA modeling forms an invaluable numerical complement to experimental slab impact testing.

4. Dynamic Response of Slabs on Elastic Foundations

4.1 Natural Frequency and Resonance Effects

The natural frequency, representing the inherent vibration mode of a structural system, wasa key dynamic response parameter for slabs on elastic foundations. The natural frequency depends on slab stiffness, foundation properties, and boundary constraints, with higher frequencies indicating greater dynamic load resistance [40, 41]. Resonance effects arise when dynamic loading frequencies coincide with natural frequencies, inducing amplified vibrations and concentrated stresses [42]. Strategies exist to mitigate resonance hazards, including added structural damping using energy-absorbing materials and damping devices to dissipate energy. Adjusting foundation properties or redesigning slabs to avoid frequency matching can also minimize resonance [43,44]

4.2 Vibration Damping and Energy Dissipation.

Vibration damping in slabs on elastic foundations enables energy dissipation through material damping, viscoelasticity, and energy-absorbing devices. Material damping, inherent in construction materials, involves mechanical-to-thermal energy conversion under dynamic excitation [45]. Viscoelastic materials, like damping coatings or pads, provide additional damping through vibration amplitude reduction [46]. Higher energy dissipation capacity confers greater resilience to impact loading [47]. Resilient bearings, isolators, or base isolation systems also effectively reduce vibrations and improve energy dissipation [48]. Retrofitting strategies often incorporate energy-absorbing materials, damping systems, or base isolation to enhance the dynamic response and resilience of foundation-supported slabs [49].

4.3 Impact Mitigation Techniques.

Impact mitigation techniques were vital for enhancing the resilience of slabs on elastic foundations and averting potential damage or failure under dynamic loads. Effective mitigation strategies empower structures to withstand impacts and ensure occupant and asset safety. Energy-absorbing materials like foams, rubber pads, and shock-absorbing coatings can be incorporated to dampen impact forces through deformation or stress relaxation, reducing force transmission to slabs [50]. Damping systems including tuned mass dampers and tuned liquid dampers absorb and dissipate impact energy [51]. Base isolation decouples slabs from ground motion using isolators between slabs and foundations, enabling relative movement and decreasing impact force transferal, thereby minimizing potential damage. [52]

4.4 Effect of Dynamic Soil-Structure Interaction

Dynamic soil-structure interaction (SSI) significantly influences the behaviour of slabs on elastic foundations under impact loads. SSI governs the dynamic response, frequencies, and energy dissipation through complex interplay between the structure and underlying soil. Elucidating SSI mechanisms was critical for accurate prediction of structural performance and safety. SSI involves multifaceted phenomena including wave propagation through soil, soil energy dissipation, and the effect of soil properties on structural response. SSI also induces coupling between the slab and surrounding soil, modifying vibration modes and frequencies [53, 54]. The frequency-dependent nature of soils crucially affects the dynamic response of slab-foundation systems. Soil stiffness and vary with loading frequency. Capturing these frequency dependencies in analysis was vital for accurately modeling SSI [55]. SSI can amplify or attenuate structural impact response based on soil characteristics and excitation frequency [56].

5. Failure Mechanisms and Critical Impact Loads

5.1 Slab Cracking and Spalling

Cracking represents a prevalent failure mode in slabs subjected to impact loading. Sudden dynamic forces, like dropped objects or vehicular impacts, can induce tensile stresses exceeding the material strength and initiating cracks. Cracking arises from:

a) Flexural cracking due to excessive bending stresses, with tensile cracks on the bottom and compression at the top surface propagating slab lengthwise [57].

b) Shear cracking when applied shear stresses surpass the shear strength, typically propagating diagonally across the slab.

Additionally, spalling was a notable impact-induced damage mechanism, whereby the concrete surface layer detaches in small fragments owing to high-energy impacts. The intense dynamic forces can cause the surface layer to break off, resulting in spalling damage [58].

5.2 Punching Shear Failure

Punching shear failure represents a critical failure mode for slabs subjected to impact loading. Concentrated loads from falling objects or high-speed impacts can induce localized stresses at slab-column interfaces, resulting in sudden punching shear failures. Elucidating the mechanisms underlying punching shear wasvital for ensuring impact-loaded slab integrity. Experimental tests by Nikpour et al [59] on reinforced concrete slabs under drop hammer impacts highlighted punching shear failure predominance. Li et al. [60] investigated punching shear in impacted fiber-reinforced concrete slabs, proposing improved design recommendations. Punching shear arises from concentrated impact forces propagating as stress waves and generating localized high stresses around supports. Exceeding the shear capacity precipitates brittle punching shear failures [61]. Studies reveal that impact loads surpassing identified thresholds substantially increase punching shear failure risks, with the critical loads depending on parameters including slab thickness, concrete strength, and reinforcements [62]. Proposed enhancements for punching shear resistance include increased slab thickness, additional shear reinforcement near supports, and high-strength concrete use in critical zones.

5.3 Progressive Collapse Analysis

Progressive collapse poses a major risk for impact-loaded slabs as critical building components. Experimental and analytical studies provide insights into slab collapse mechanisms and load redistribution under impacts. Huang et al. [67] experimentally assessed reinforced concrete slab progressive collapse resistance under impacts, elucidating failure modes and redistribution behaviour. Wang et al. [68] proposed finite element simulation methodologies to investigate slab collapse under impacts. Localization of impact forces and moments can initiate failure at specific slab zones, with failed region loads redistributing to other areas, potentially triggering progressive collapse. Impact load dynamics further complicate collapse assessments [69]. Calibrated finite element models complement experiments by enabling detailed examinations of progressive collapse mechanisms through parametric studies on design factors influencing slab collapse resistance [70].

Proposed impact-resistant design measures include redundancy, slab-to-element connection enhancement and, optimized reinforcement for improved load redistribution [71].

5.4 Slab-Foundation Separation

Slab-foundation separation represents a severe failure mode for impact-loaded slabs, involving detachment between the slab and foundation due to excessive impact forces. Studies by Kim et al. [63] highlighted the significance of slab-foundation separation as an impact-induced failure mode. Additionally, Lee et al. [64] provided insights into the interface behaviour and separation mechanisms under dynamic loads.

Typically, high interface stresses and displacements from impact events lead to cracking and debonding, causing load transfer loss and subsequent slab detachment. The dynamic nature of impacts exacerbates these effects, precipitating rapid separation [65]. Critical impact loads depend on parameters including slab and foundation properties, slab thickness, and support conditions. Design considerations involve adequate reinforcement and anchorage to resist dynamic separation forces [66].

6. Design Considerations for Slabs under Impact Loading

Designing slabs to withstand impact loading was crucial for ensuring the safety and structural integrity of the entire building. This section will explore various design considerations that should be taken into account when designing slabs to resist impact loads effectively.

6.1 Load Estimation and Load Distribution

Impact load estimation for slabs necessitates determining load types and magnitudes based on impactor mass, velocity, height, and other parameters using empirical data, experiments, or simulations [72]. As dynamic loads, impacts impart higher forces than equivalent static loads.

Dynamic load factors account for impact duration and frequency, converting dynamic loads into equivalent static loads for analysis [73]. Load distribution paths critically transfer impact loads from the application point through the slab into the supporting structural system and foundation. Paths should minimize stress concentrations and enable efficient load transfer [65].

6.2 Reinforcement Strategies

Multiple reinforcement strategies can enhance slab impact resistance:

- Increased bottom reinforcement improves tensile capacity, crack resistance, and failure prevention under tension from impacts [74].
- Proper shear reinforcement detail, like stirrups or transverse bars, augments shear resistance to mitigate common punching shear failures [75].
- Steel fibers or mesh added to concrete increase crack resistance, post-cracking ductility, toughness, and energy absorption [76].
- Ductile reinforcement detailing enables controlled deformation and energy dissipation through reinforcing bar yielding or ductile connectors to prevent sudden failure [77,78].

Experimental and analytical studies had revealed various reinforcement approaches, including augmented bottom bars, shear elements, steel fibers/mesh, and ductile details, that improve slab performance, toughness, and failure resistance when subjected to dynamic impact loads.

6.3 Retrofitting and Strengthening Techniques

Various retrofitting and strengthening techniques can enhance the impact resistance of existing slabs by improving structural capacity, ductility, and energy dissipation:

- External steel plating or shear reinforcement increases flexural and shear capacities while distributing loads to mitigate localized stress concentrations under impact [79].
- Fiber reinforced polymer (FRP) materials like carbon or glass fibers bonded with polymer resins provide lightweight slab strengthening when externally bonded or near-surface mounted. FRP enhances tensile and flexural capacities, preventing sudden failure [80].
- Added steel mesh or fibers as surface reinforcements or cast into the concrete mix improve slab toughness and crack resistance to better distribute and absorb impact energy [81].
- Providing additional support or connection details improves load distribution and transfer. Strengthening slab-column and slab-beam connections prevents premature detachment under impacts
- External reinforced concrete jackets constructed with bonded concrete layers increase slab strength, durability, and load capacity.

Experimental and analytical studies had demonstrated the effectiveness of retrofitting methods including supplemental external or near-surface reinforcement, FRP bonding, and cast-in steel mesh/fibers for strengthening existing slabs against impact loads. The techniques aim to enhance slab structural integrity for resilient resistance to dynamic impacts.

7. HPC and UHPC Slabs under Impact Loads

The behaviour of concrete slabs under impact loading is a subject of paramount importance in structural engineering, particularly in contexts where dynamic forces pose significant risks. The response of these structural elements to sudden, high-intensity loads varies markedly depending on the type of concrete employed. This discourse aims to elucidate the distinctions between standard concrete, High-Performance Concrete (HPC), and Ultra-High-Performance Concrete (UHPC) slabs when subjected to impact loading, drawing upon recent research and empirical observations. Slabs with normal concrete when subjected to dynamic forces typically display a relatively brittle behaviour [82]. This brittleness is characterised by the rapid propagation of cracks which often leading to extensive spalling and in severe cases catastrophic failure. The energy absorption capacity of standard concrete is limited. This resulting in a significant portion of the impact energy being transferred to the supporting normal concrete structures [83].

Moreover, the strain rate sensitivity of standard concrete is pronounced with its strength and stiffness properties showing marked increases under high loading rates [84]. This phenomenon potentially beneficial in some respects which lead to unpredictable behaviour and complicates the design process for impact-resistant structures. Whereas High-Performance Concrete (HPC) represents a significant advancement over standard concrete in terms of impact resistance. HPC is characterised by its enhanced strength, typically achieved through the optimisation of the mix design and the incorporation of supplementary cementitious materials such as silica fume and the fly ash. The improved mechanical properties of HPC translate to superior behaviour under impact loading. HPC slabs generally exhibit higher energy absorption capacities and reduced cracking propagation compared to the normal concrete counterparts [85, 86]. The enhanced durability of HPC also contributes to its improved impact resistance, as the denser microstructure and reduced permeability limit the ingress of deleterious agents that could compromise the slabs integrity with time [87].

The behaviour of HPC slabs under impact loading is further distinguished by their enhanced strain rate sensitivity. Research showned that the dynamic increase factor for compressive strength in HPC can be significantly higher than that of standard concrete

[88]. This property allows HPC slabs to better resist the high-intensity stresses generated during impact events. Additionally, the improved bond strength between reinforcement and concrete in HPC leads to more effective load transfer and energy dissipation mechanisms [89]. Consequently, HPC slabs often display more distributed damage pattern under impact loading with multiple smaller cracks as opposed to the few large cracks typically observed in standard concrete slabs. Similarly, Ultra-High-Performance Concrete (UHPC) represents the pinnacle of concrete technology in terms of impact resistance. The behaviour of UHPC slabs under impact loading is markedly superior to both standard concrete and HPC slabs, exhibiting unprecedented levels of energy absorption and damage resistance. The exceptional performance of UHPC slabs under impact can be attributed to several factors. Firstly, the ultra-dense microstructure of UHPC, achieved through optimised particle packing and very low water/binder ratios, resulting in a material with minimal porosity and exceptionally high strength [90, 91]. Similar to HPC, the dense matrix of UHPC provides superior resistance to crack initiation and propagation. Secondly, the incorporation of high volumes of steel fibres (typically 2-3% by volume) imparts significant ductility and tensile capacity to the material [92]. These fibres act to bridge micro-cracks, allowing for the development of multiple cracking under impact and significantly enhancing the energy absorption capacity of the slab. The strain rate sensitivity of UHPC is particularly noteworthy. Studies have shown that the dynamic increase factor for both compressive and tensile strengths in UHPC can be substantially higher than those observed in standard concrete or HPC [93]. This pronounced strain rate effect contributes to the material's exceptional performance under high-velocity impacts. Furthermore, the fibre reinforcement in UHPC plays a crucial role in energy dissipation during impact events. The pullout and yielding of steel fibres consume significant amounts of energy, contributing to the material's ability to withstand repeated impacts without catastrophic failure [94].

The failure mode of UHPC slabs under impact loading is distinctly different from that of standard concrete or HPC slabs. While the latter may exhibit punching shear failure or extensive cracking, UHPC slabs often display a more localised damage pattern with minimal spalling [95]. The high tensile strength and ductility of UHPC allow for the development of membrane action in the slab, which can significantly enhance its load-carrying capacity under large deformations. It is crucial to note that the superior performance of UHPC comes at a considerable cost premium compared to standard concrete or HPC. The complex mix design, specialised production processes, and high fibre content contribute to significantly higher material costs [95, 97]. However, in applications where impact resistance is paramount, such as protective structures or critical infrastructure, the enhanced performance of UHPC may justify the additional expense.

8. Conclusion

This review paper aims to serve as a valuable resource for researchers and engineers involved in the design and assessment of slabs subjected to impact loading. By consolidating findings from a wide range of studies, the paper addresses key knowledge gaps, highlights challenge:

a) Higher natural frequencies indicate increased stiffness and better resistance to dynamic loading,
b) Vibration damping mechanisms and energy dissipation capacity improve the structural resilience and reduce the risk of failure.
c) Vibration isolation techniques and retrofitting strategies can further improve the dynamic response.
d) Advanced techniques, such as digital image correlation and structural health monitoring, had significantly contributed to quantifying and evaluating the extent of damage in slabs.
e) Concrete strength, reinforcement detailing, material ductility, toughness, anisotropy, heterogeneity, and strain rate sensitivity play essential factors in determination of the impact resistance.
f) Punching shear failure is a crucial failure mechanism for slabs subjected to impact loads.
g) Progressive collapse analysis of slabs under impact loads was crucial for ensuring the safety and resilience of structures.
h) Reinforcement configurations play a vital factor that provide resistance of slabs under impact loading
i) Retrofitting and strengthening techniques were valuable tools for upgrading existing slabs to withstand impact loading.

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