



Dynamic Response and Reliability Assessment of Reinforced Concrete Members Under Vehicle and Train Collisions: Quantifying Impact Performance and Damage

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Abstract. This study analyzes the behavior of reinforced concrete (RC) members impacted by vehicles or trains by reviewing existing experimental and numerical work. RC structures are susceptible to such collisions, which can cause structural failure or collapse. The damage response depends on the energy transferred during impact, ranging from cosmetic effects to full structural failure. To properly characterize damage, indices are defined considering concrete and steel strain rates during and after plastic deformation. Concrete spalling is also discussed as an indicator of localized or global failure severity. Experimental results from other studies are presented and compared to theoretical models. The latest provisions for incorporating strain rate sensitivity into material models based on various standards are reviewed. This analysis aims to provide insights for better assessing the reliability of RC members after impacts. Understanding reliability is important for evaluating the safety of damaged structures and mitigating risks. The findings can help practitioners evaluate damaged structures and guide future design to avoid severe outcomes from vehicle and train collisions onto critical infrastructure.

Keywords: Unequal Impact · Shear Failure · Strain Rate · Crack Propagation · Numerical Analysis · Bending Failure

1 Introduction

Lateral impact loads such as earthquakes, explosions, vehicle collisions, train impacts, and ship impacts can cause significant damage to reinforced concrete (RC) structures if not properly addressed in the design [1, 2]. RC structures are composed of concrete and steel reinforcement and are designed to resist compressive and tensile forces. However, lateral loads induce complex stress states that can exceed the strength of materials [3, 4]. Understanding how RC structures behave under these dynamic loads is important for safety and performance. Several factors influence the response to lateral impacts. The strength of the concrete and steel reinforcement is critical, as higher

material strengths improve impact resistance [5, 6]. The compressive strength of concrete and tensile strength of reinforcing steel allows the structure to withstand greater loads. Larger cross-sectional dimensions and more reinforcement provide better protection against impacts [7, 8]. The intensity and duration of lateral loads also matter [9, 10]. Short, high intensity impacts from explosions often cause the most damage through cracking and spalling of concrete cover [11, 12]. Proper design must consider load characteristics [13, 14]. In comparison, longer earthquake loads typically induce less severe cracking. Proper design must consider load characteristics. Research into RC structural behavior under lateral loads occurs through experimentation and numerical modeling. Full-scale and small-scale impact tests using methods like drop-weight impact dynamic loads [15, 16]. Observations from these experiments enhance understanding of RC response. Numerical simulations employ tools like finite element analysis to replicate complex loadings in a controlled virtual environment [17, 18]. Blast loading is an extensively researched lateral impact. Studies show explosives induce cracking and reinforcement failure. Parameters like explosive type/size/location and structure properties yield valuable data. High-strength concrete and reinforcement performed better. Train and ship collisions are also under examination. Varying cross-sectional geometries, vehicle velocities, material properties, and impact zones alter the structural response. Cracking and spalling patterns emerge depending on parameters. Advancing knowledge aims to refine modeling accuracy and develop improved designs. Fiber-reinforced polymers show promise as alternative reinforcement. Innovations target handling impacts without failure to safeguard infrastructure. As lateral impacts endanger the integrity, ongoing work strives to comprehend failure mechanisms better. The goal is to design RC members efficiently to withstand dynamic hazards through resistance strategies. Deeper insight supports assessing damaged structures and mitigating life safety risks from impact incidents. Continued research in this vital field fortifies resilient construction.

2 Collision Incidents

Vehicle-structure and train-structure collisions are unfortunate but relatively common incidents that can lead to loss of life, injury, and property damage if not properly addressed. As transportation and infrastructure development continues globally, protecting against these hazards grows more important. Collisions can occur in various scenarios. Due to driver error or vehicle malfunction, cars or trucks may crash into bridges, buildings, or guardrails. Derailed trains can impact a rail network's bridge piers, walls, or other fixed concrete assets. Ships navigating waterways also pose collision risks with bridges under some conditions. Several high-profile incidents demonstrate the destructive potential. In 2007, the cargo ship *Cosco Busan* struck a San Francisco Bay pier, resulting in an oil spill and over \$70 million in cleanup costs. In China, fatal train wrecks between 2011–2018 involving reinforced concrete bridges caused hundreds of casualties [2]. Other cases internationally include trains hitting walls in Spain, the USA, and Turkey with loss of life. Factors contributing to accidents span both human factors and structural/design elements. Poor driving, train operations errors, mechanical failures, and unexpected natural events can all trigger impact scenarios. Infrastructure layout,

bridge/wall placements, and wind/sea conditions in maritime settings also influence collision likelihood. Impacts create considerable damage depending on vehicle/vessel mass and velocity.

3 Methodology

The methodology used in a literature review is critical to its success and credibility. The methods and techniques used in a literature review determine the quality and relevance of the research sources reviewed and, thus, the validity and reliability of the findings. This paper describes the methods and techniques used in the literature review on RC structures subjected to lateral impact loads. The paper will include the databases, search terms, and inclusion and exclusion criteria. This paper used several databases, including the Web of Science, ScienceDirect, and Scopus. The databases were searched using the following terms: “reinforced concrete, lateral impact loads, blast loads, vehicle impact loads, train impact loads, ship impact loads, seismic loads, behavior, performance, damage.” The article was limited to the last twenty years to ensure that the most recent research was included in the review. The paper included studies published in peer-reviewed journals, conference proceedings, and dissertations. The studies had to be in English and focused on the behavior of RC structures under lateral impact loads. The studies also had to include experimental or numerical analysis of the behavior of the structures. The studies included in this paper were analyzed systematically and comprehensively. The studies were first grouped into categories based on the type of lateral impact loads they addressed (blast, vehicle, train, ship, seismic). Then, the studies were reviewed, and their main findings were extracted and summarized. The studies were also compared to identify similarities and differences in their conclusions.

4 Investigating the Results of Impact Resistance on RC Members: A Study of Experimental, Numerical, and Analytical Methods

Reinforced concrete members are prone to severe damage from impact accidents, which can cause partial failure or collapse of the structure. Scholars have studied impact resistance through experiments, numerical analysis, and analytical methods.

4.1 Experimental Analysis

Research on the dynamic response of reinforced concrete members to impact loads has provided valuable insights but is limited by testing constraints. Most studies focus on mid-span impact, but parameters like boundary conditions, impactor shape, and impact position require further examination. Hughes and Speirs [3] conducted impact tests with varying support conditions and local stiffness. Members failed in bending concentrated at supports and mid-span. Stiffness had more influence on response than support. Demartino tested cantilevers and simply supported beams, finding boundary conditions and velocity greatly affected response and damage. Measured inertial forces indicated they resist over 2/3 of peak impact load. Pham and Hao [4] proposed models considering

impact, support, and inertial forces. The failure occurred via bending and shear beyond concrete grades of 46MPa or collapse between 60-100MPa. Stress wave propagation generates local response, while global behavior is more important per another research. Impact body shape had little effect on overall resistance, according to some [5]. Axial load positively influenced minimum deformation but caused catastrophic failure at high velocity with low reinforcement. The shear failure occurred below static capacity. Varying impact velocity produced differing crack patterns - oblique cracks near impact (Type I) for high velocity, like static tests for inclined cracks (Type II). Type I was unique to impact. Reinforcement ratio and member grade influenced failure mode and response [6]. Further studies aim better to characterize dynamic reinforced concrete behavior under impact loads.

4.2 Numerical Analysis

Finite element software like ABAQUS, LS-DYNA, and ANSYS have become increasingly popular among scholars since the 1990s. Numerical simulation methods are widely used to simulate explosion and impact behavior in civil engineering [7–9] and to obtain essential conclusions about members' responses under impact load. The constitutive relationship under dynamic material load plays a vital role in numerical analysis. Constitutive relationship under a dynamic load of materials. Steel bars exhibit different mechanical properties under dynamic and static loading. The strain rate effect is significant under dynamic load and increases the yield strength more than the ultimate strength. Other models have been proposed to describe this effect, such as the Cowper-Symonds and Johnson-Cook models, which scholars widely recognize [10, 11].

$$\sigma = \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{p}} \right] \sigma_0 \quad (1)$$

where σ is the stress of the steel under static loading, $\dot{\epsilon}$ is the plastic strain rate, σ_0 is the stress of the steel under static loading, C and p are the parameters models related to the type of material. This model can estimate the dynamic yield strength and ultimate strength of steel at a given strain rate and is suitable for describing the strain rate effect of steel at lower strain rates. Johnson-Cook calculation formula of the model is as follows:

$$\sigma = (A + B\epsilon^n)(1 + C \ln \dot{\epsilon}^*) (1 - T^{*m}) \quad (2)$$

$\dot{\epsilon}^* = \dot{\epsilon} / \dot{\epsilon}_0$, $\epsilon_0 = 1S^{-1}$, T^* is a function of temperature, and A , B , C , n , and m are model parameters related to material properties. The first bracket in the formula indicates the stress-strain relationship at $\dot{\epsilon}^* = 0$, $T^* = 0$, the second bracket indicates the strain rate effect, and the third bracket indicates the temperature effect. Early studies showed concrete strength increases with higher strain rates, though the degree depends on factors like static strength and rate magnitude. Abrams [12] found strength rose from $2 \times 10^{-4}/s$ to $8 \times 10^{-6}/s$ testing in 1917. Bischoff and Perry [13] analyzed data, finding strength grows more gradually below a critical rate but rapidly exceeds it. Atchley and Furr [14] found ultimate strength plateaued at high rates, possibly due to different strain measurement locations. Jia et al. [15] found low temperatures boosted strength with

rising rates, s but high heat weakened it, as cracks formed beforehand, preventing rate effects. Cotsovos and Pavlovic [16] showed via modeling that local regions experience differing mechanical states in rapid tests, implying rate impact's structure rather than just material performance. Debates remain around whether strength boosts arise from direct rate impacts or confinement pressures in experiments. The most common design strength calculation comes from the CEB-FIP [17] Model Code fitted to test data. While mechanical properties under rapid loading are well-researched, controversies persist around strain rate effect mechanisms on concrete strength. Further studies could provide clarification.

$$\frac{\sigma_d}{\sigma_s} = \begin{cases} \left(\frac{\dot{\epsilon}_d}{\dot{\epsilon}_s}\right)^{1.026\alpha} & \dot{\epsilon}_d \leq 30s^{-1} \\ \gamma \left(\frac{\dot{\epsilon}_d}{\dot{\epsilon}_s}\right)^{1/3} & \dot{\epsilon}_d > 30s^{-1} \end{cases} \quad (3)$$

σ_d is the compressive strength of concrete under dynamic loading, σ_s is the compressive strength of concrete under static loading, $\dot{\epsilon}_d$ is the strain rate value under static loading. The parameters α , γ values are specified in the specification. Research on concrete dynamic tensile properties also shows strength increases with higher strain rates. Hopkinson bar testing is commonly used. Malvar and Ross [18] found tensile strength grows more gradually below a critical rate before rapidly rising above it, similar to compression. Ross [19] determined strain rate had a greater impact on tensile versus compressive strength. Yan and Lin [20] studied how properties like strength, modulus, peak strain, and energy absorption changed with loading rate, temperature, and moisture content. Saturated concrete strength increased more substantially. Some debates exist around whether increased tensile strength stems from inertia effects or actual material behavior. Lu and Li [21] proved through modeling that increased strength was not due to higher simulated rates, indicating actual material behavior causes strengthening. The commonly used CEB-FIP [17] Model Code proposes a calculation formula to estimate dynamic tensile strength based on static properties and strain rate. Research continues to enhance understanding of concrete behavior under rapid tensile loading.

$$\frac{f_{ct,imp}}{f_{ctm}} = \begin{cases} \left(\frac{\dot{\epsilon}_{ct}}{\dot{\epsilon}_{ct0}}\right)^{1.026\alpha} & |\dot{\epsilon}_{ct}| \leq 10s^{-1} \\ 0.0062 \left(\frac{\dot{\epsilon}_{ct}}{\dot{\epsilon}_{ct0}}\right)^{1/3} & |\dot{\epsilon}_{ct}| > 10s^{-1} \end{cases} \quad (4)$$

$f_{ct,imp}$ is the tensile strength of concrete under dynamic loading, f_{ctm} is the tensile strength of concrete under static loading, $\dot{\epsilon}_{ct}$ is the material strain rate, and $\dot{\epsilon}_{ct0}$ is the strain rate value under static loading.

4.3 Response of Members Under Impact Load

Cai et al. [22] used ABAQUS to simulate the dynamic response of 7 reinforced concrete members with a section size of 150 mm × 150 mm under low-speed horizontal impact loads. The authors studied the effect of impact mass and velocity on the failure mode of members. It is found that the inertia effect has a significant impact on the impact

resistance of the member. By finite element analysis, Yu et al. [23] proposed simultaneously considering the effect of the impact body mass and velocity on the reinforced concrete member. Once the impact body mass and velocity are small, the maximum and residual deflection of the member is greater. EL-Tawil et al. [24] used the finite element simulation method to study the dynamic response of the bridge pier after being hit by a vehicle. The finite element method simulates the impact of heavy trucks' reinforced concrete members with square and circular cross-sections. The members' heights are 16.3 and 9.9 m, and the impact velocities are 1.35 m. The effects of different impact masses and velocities on reinforced concrete members' dynamic responses are analyzed. The results show that the equivalent static force calculation method proposed by AASHTO-LRFD [25] is not conservative in estimating the design force of an overweight truck hitting a bridge pier. To evaluate the vulnerability of reinforced concrete members to vehicle collisions, Thilakarathna et al. [26] established a numerical model of full-scale reinforced concrete members with circular cross-sections under an impact force. The mid-span deflection and bearing reaction force test data verify the model's accuracy. A method that can quantify the degree of damage to reinforced concrete members is proposed. Study the reinforced concrete members' dynamic response and failure mode under impact with and without CFRP layers. The experimental method and finite element analysis show that the CFRP reinforcement can change members' failure modes. The failure mode of reinforced concrete members that undergo shear failure under unequal span lateral impact load hitting by a derailed train is transformed into flexural failure after being wrapped by CFRP layers, as shown in Fig. 1 [27–35].

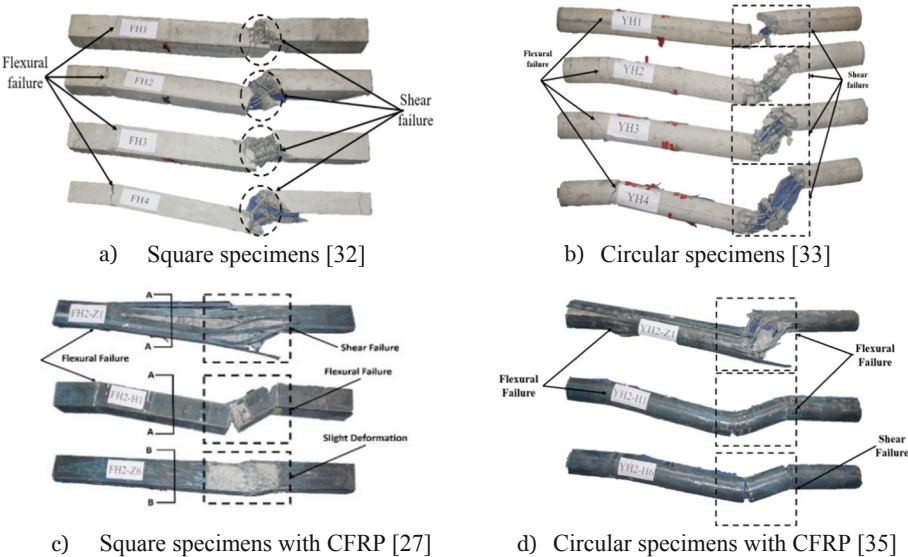


Fig. 1. Failure modes after the end of the impact scenario

5 Discussion

This section will discuss the key findings from the literature review in more detail and highlight important themes. One of the most prominent findings is that steel reinforcement and high-strength concrete are effective techniques for mitigating impact loads on RC structures. Several studies demonstrate their abilities to improve impact resistance by reducing cracking, spalling, and reinforcement failure [3, 4, 6]. However, the degree of benefit depends on factors like reinforcement ratio and impact parameters. Further research is still needed to optimize design guidelines around these techniques. Numerical simulation methods like finite element analysis were commonly used and provided valuable insights. However, the accuracy of such models relies on the constitutive relationships used to define dynamic material behavior under high strain rates. While extensive research has enhanced our understanding of rate effects, controversies remain around the mechanisms influencing concrete properties. More work is needed to clarify these issues and improve constitutive models. Regarding structure types, buildings, and bridges received the most attention due to their vulnerability. However, other structures like retaining walls are also at risk but lack comparable study. Combined loads and long-duration impacts were identified as prominent gaps. Considering multiple hazards simultaneously is important for robust design but challenging to reproduce experimentally. Classification systems for different failure patterns aim to aid damage evaluation but require further validation and standardization. Correlating measured response to specific performance limits would strengthen their practical application.

The discussion section of this paper presents the main findings, including the types of RC structures most studied and the most effective techniques for mitigating the effects of lateral impact loads. This section also highlights any major gaps in the literature and identifies areas for future research. In addition, this review aims to determine whether it has filled any knowledge gaps not addressed by previous studies. This paper aims to present the main findings of the literature review on RC structures subjected to lateral impact loads and discuss any major gaps in the literature. Buildings and bridges are the most studied RC structures concerning lateral impact loads. These structures are particularly susceptible to damage from blasts, vehicles, trains, ships, and seismic loads. Furthermore, it suggested that steel reinforcements and high-strength concrete effectively mitigate lateral impacts on RC structures. Several studies have found that using high-strength concrete and steel reinforcement improves the ability of the structures to withstand lateral impact loads, reducing cracking and spalling of the concrete and failure of the steel reinforcement. This review paper also revealed that numerical analysis, such as finite element analysis, is a commonly used technique for studying the behavior of RC structures under lateral impact loads. These techniques allow for the simulation of different loading scenarios, providing valuable insights into the behavior of the structures under different types of loads and conditions. The article revealed several gaps in the current research on RC structures subjected to lateral impact loads. One major gap is the lack of research on the behavior of RC structures under combined loads, such as simultaneous blast and seismic loads. In addition, there is a lack of research on the behavior of RC structures under long-duration loads, such as those caused by prolonged vehicle or ship impact. Another gap in the literature is the lack of research on the behavior of RC structures under different types of lateral impact loads, such as those caused by aircraft

impact. Additionally, there is a lack of research on the behavior of RC structures caused by derailed train impact.

6 Conclusion

The conclusion of this paper is crucial in summarizing the main findings of the research and providing recommendations for future research on the topic. This paper summarized the main findings of the literature review on RC structures subjected to lateral impact loads and provided recommendations for future research. The article also emphasized the importance of continued research to improve the design and performance of RC structures subjected to lateral impact loads. The specific contributions outlined damage responses, failure patterns, real-world incidents, material behavior insights, and remaining research gaps in this field. Providing a comprehensive review of the damage responses of RC members to various lateral impact loads such as vehicle, train, and ship collisions based on existing experimental and numerical studies. Various performance-based studies were examined to find the best way to predict damage. Classifying different failure patterns of RC members under impact loads based on damage severity can help evaluate structural integrity after a collision event. Highlighting real-world collision incidents to demonstrate the destructive potential of such accidents and the need to improve impact resistance of infrastructure. Summarizing the latest understandings of material behavior under high strain rates from the literature to inform more accurate simulation of impact load scenarios. Identifying remaining gaps in research, such as the behavior of combined loads, to guide future work towards more robust assessment and design for impact resistance.

Two alternative configurations of RC columns were used in each case. According to the findings of the research topic, the impactor speed is related to the duration for which the peak impact force is generated. This article also includes experimental and numerical findings on the effects of drop hammer impact weight on columns and beams. Finally, when comparing dynamic and impulsive testing to quasi-static testing, it seems that concrete materials exhibit an apparent increase in strength. Much test data documented in the article regarding strain rate sensitivity has been discussed. Moreover, more modeling studies and field testing are needed to develop the dynamic response methodology that precisely evaluates the damage of RC members by impact force and improves decision-making on what must be done to protect the RC members from impact force damage.

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