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Review Research Paper

Improving the Blast Resistance of Reinforced Concrete Columns: A Literature Review

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ABSTRACT

This study demonstrates the combination of experimental and numerical analyses to advance the understanding and design of blast-resistant reinforced concrete (RC) columns. Experimental research provides crucial empirical data on the dynamic behavior of RC columns subjected to blast loads, capturing parameters such as deformation, displacement, strain distribution, and failure patterns. These data are essential for the validation and calibration of numerical models. Numerical simulations, using sophisticated computational methods like finite element analysis (FEA), offer a controlled and cost-efficient way to investigate various blast conditions, including different intensities, impact angles, and column configurations. The integration between experimental and numerical methods is essential for developing effective strategies to enhance the blast resistance of RC columns, ensuring the safety and stability of critical infrastructure. This paper reviews various studies conducted over time, emphasizing the influence of different strengthening techniques in resisting blast impacts.

Introduction

Understanding Blast Loads

Blast loads, defined by the rapid and intense pressures resulting from releasing explosive energy, impose considerable challenges to the structural integrity and safety of buildings and infrastructure. These loads, which are characterized by high pressure, shock waves, very small duration, and high impulse, can arise from sources such as terrorist attacks, industrial accidents, or military operations. The interaction of blast waves with their environment leads to phenomena like refraction and reflection, can intensify and increase the impact of blast loads. Structures exposed to blast waves may also experience secondary impacts; including fire, debris, and fragmentation, further compounding the damage. These secondary hazards not only increase structural damage but also heighten risks for emergency responders and occupants. Understanding the features of blast loads is crucial for assessing their impact on structures, developing appropriate mitigation strategies to enhance resilience, and ensuring the safety of occupants and key infrastructure during explosive events. Various methods are used to reduce the effects of blast loads. These strategies include emergency planning, the use of different materials as jacketing, blast-resistant designs, protective barriers, and structural reinforcements. The application of these methods, along with comprehensive investigations, can significantly reduce the risks associated with blast loads, protecting both lives and property in the event of such incidents[1], [2], [3]As shown in Figure 1

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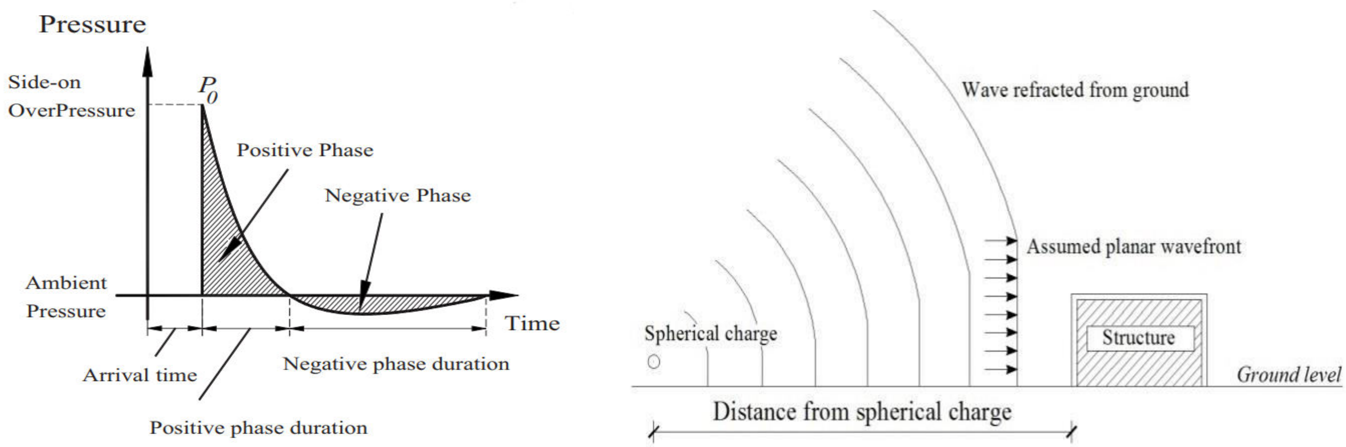

Fig 01 Blast load diagram[4], [5]

Blast Loads Effects on RC Columns

Blast loads on reinforced concrete (RC) columns pose significant risks to the structural integrity and safety of buildings and infrastructure. RC columns subjected to such loads can experience various forms of damage, including concrete spalling, cracking, crushing, and harm to the embedded steel reinforcement. The extreme pressures and shock waves produced by explosions can cause localized failures in the column, compromising its structural stability and load-bearing capacity. These damages may trigger a progressive collapse, where the failure of one element leads to the eventual failure of the entire structure.[6] Additionally, explosions significantly weaken the ability of reinforced concrete (RC) columns to withstand lateral forces such as wind or seismic loads, as well as their vertical load-bearing capacity. Additionally, these damaged structures become more vulnerable to secondary hazards like corrosion or fire, which can further threaten their stability, potentially leading to complete collapse if not properly addressed. When RC columns are exposed to blast loads, progressive failure becomes a serious concern. The sudden loss of a crucial support element due to blast-induced damage can lead to a cascade of overloading failures, as adjacent structural members are forced to bear excessive loads. This chain reaction compromises the building's structural integrity, potentially resulting in partial or total collapse in a very short time. The progressive collapse of a building can have catastrophic consequences, including the large-scale loss of life, destruction of property, and severe economic and societal impacts. To address these challenges, it is essential to implement robust strengthening techniques that enhance the blast resistance of RC columns. Engineers play a crucial role in designing structures capable of withstanding explosive events by understanding the effects of blast loads on reinforced concrete. Strong design principles, combined with effective reinforcement measures, should be incorporated to improve load-bearing capacities and increase flexibility, thereby reducing the likelihood of progressive collapse during terrorist attacks or accidental explosions[7], [8], [9].

Significance of Reinforced Concrete Columns

Reinforced concrete (RC) columns are essential structural elements used in various construction projects, including residential buildings, bridges, and high-rise structures, due to their strength and durability. Composed of concrete that encases steel reinforcement bars, RC columns possess the ability to support substantial vertical loads while efficiently transferring the weight of floors, walls, and roofs to the foundation, ensuring the overall stability and integrity of buildings. Beyond handling standard loads, RC columns also play a crucial role in resisting extreme forces, such as those generated during blast events. Their ability to withstand explosions is particularly critical in regions prone to terrorist attacks or natural disasters, such as earthquakes[10], [11].

The capacity of reinforced concrete (RC) columns to resist blast loads is crucial, as powerful explosions can result in the total collapse of buildings. When a bomb detonates, it releases energy rapidly, generating shock waves that apply immense pressure on structural components. Given that RC columns are primary load-bearing elements, they are particularly vulnerable to these intense forces. The failure of these columns can initiate a progressive collapse, leading to widespread damage or even the complete destruction of a building. Therefore, it is essential to implement protective measures against blast loads to ensure the safety of occupants and maintain the functionality of critical systems within the structure[12].

Retrofitting reinforced concrete (RC) columns for blast resistance requires a deep understanding of the dynamic nature of blast loads. Unlike static loads typically considered in structural design, blast loads are characterized by high-pressure peaks of short duration, demanding that RC columns possess significant strength and ductility to absorb and dissipate energy without failure. Therefore, it is essential to carefully assess material properties, cross-sectional dimensions, and the interaction between concrete and steel reinforcement. Enhancing the blast resistance of RC columns not only protects human lives but also strengthens the resilience of the built environment. This ensures the continued operation of critical facilities, such as hospitals, government buildings, and transportation hubs, where rapid recovery is vital. The importance of these structures extends beyond their immediate function, influencing community safety on a broader scale. Prioritizing the design of blast-resistant columns helps mitigate the impact of explosions and fortifies systems against potential future threat[13], [14].

Importance of Strengthening RC Columns

It is essential to protect the structural integrity of RC columns and ensure occupant safety in the event of explosions by enhancing their strength to withstand blast loads. RC columns are particularly vulnerable to blast-induced high-pressure waves and shocks, which can lead to significant damage. Without adequate reinforcement, such failures may be localized or escalate to a point where the columns' load-bearing capacity is severely diminished, posing risks to both the occupants and critical public facilities. Techniques such as steel jacketing, fiber-reinforced polymers (FRP), and ultra-high performance concrete (UHPC) are commonly employed to increase the blast resistance of these structural members. When applied effectively, these methods not only mitigate the impact of explosions on buildings but also enhance overall structural strength, preventing collapse under extreme conditions like earthquakes or hurricanes. By prioritizing these strengthening measures, engineers can significantly improve the resilience of RC columns against blast loads, thereby ensuring safety in hostile situations[15], [16].

Strengthening RC columns

Different Strengthening Methods

Steel Jacketing

Steel jacketing is a traditional method used to improve the strength of RC columns, particularly in structures susceptible to blast loads. This technique involves encasing the existing RC column with steel plates or sections, forming a protective outer layer of steel around the column. The primary goal is to enhance the columns' toughness, rigidity, and load-bearing capacity. The steel jacket serves as a protective shield, providing greater strength than concrete alone, as steel is highly resistant to tensile stresses that could otherwise lead to early failure or collapse. Furthermore, the confinement provided by the jacket improves the concrete's ability to withstand lateral forces, contributing to the overall stability of the building system. In addition, steel jackets often have corrosion-resistant properties, reducing the impact of environmental factors and extending the service life of the columns, which in turn helps lower maintenance costs.[17], [18]. Figure 2 shows steel jacket retrofitting of an RC member.

Fig 2 Steel Jacketing of RC member [19]

Fiber Reinforced Polymers (FRP)

Fiber Reinforced Polymers (FRP) have gained popularity as an effective method for retrofitting RC columns to withstand blast loads due to their unique properties and adaptability. These materials consist of high-strength fibers, such as carbon, glass, or aramid, embedded within a polymer matrix, typically epoxy resin. The combination of these components results in lightweight yet highly durable composites. FRP's exceptional strength-to-weight ratio is a key factor in its ability to resist blasts, allowing forces to be efficiently distributed across a structure without adding significant weight. This makes FRP ideal for reinforcing existing concrete columns without increasing the dead load of the building. Additionally, FRP's excellent corrosion resistance ensures long-term durability, particularly in harsh environments, such as coastal or industrial areas, where exposure to moisture, chemicals, and salt can cause conventional materials like steel to deteriorate. The versatility of FRP in accommodating various column shapes and sizes also makes it an ideal solution for blast-resistant projects. The material can be easily molded or wrapped around existing RC members, ensuring uniform strength distribution across the surface, rather than concentrating on specific points, thereby enhancing overall structural performance.[20], [21], [22]Figure 3 shows a scheme of using FRP jacketing of RC members.

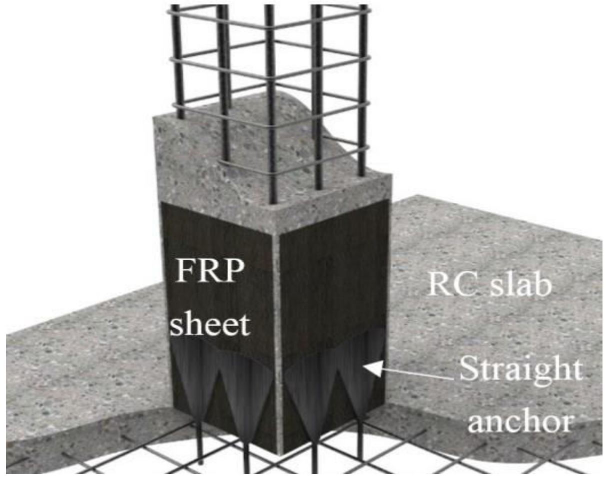

Fig 0 Scheme of using FRP for retrofit of RC member [23]

Experimental Studies

The advancement of blast-resistant structures, particularly for reinforced concrete (RC) columns, heavily relies on the integration of experimental research. This approach assesses the dynamic behavior of RC columns under blast loads by utilizing empirical data gathered from controlled lab experiments or field testing. Equipped with advanced tools like high-speed cameras, strain gauges, and pressure sensors, experimental studies are crucial in understanding the real-world response of RC columns to explosive forces. These investigations provide critical insights into deformation, displacement, strain distribution, and failure mechanisms, which form the foundation for calibrating and validating models, ensuring their accuracy and reliability. Through these experiments, researchers can observe the pre-blast and post-blast conditions of RC columns, gaining valuable insights into the resulting physical changes and damage patterns. This data helps identify vulnerable areas that are in need of strengthening and informs the design of more blast-resistant structures. Additionally, experimental studies enable the assessment of various strengthening methods, such as fiber-reinforced polymers (FRP) and steel jacketing, by testing RC columns under different blast conditions. Researchers can evaluate how these techniques enhance structural resilience and integrity. Ultimately, the knowledge derived from experimental research is pivotal in developing standards and guidelines for designing blast-resistant structures, ensuring the safety and stability of buildings and infrastructure in the event of explosive incidents[23], [24]. Over time, various techniques have been employed for retrofitting RC columns. In 2015, Jacques et al. conducted experimental tests on reinforced concrete (RC) columns retrofitted with glass-fiber-reinforced polymer (GFRP) and subjected to simulated blast loads. Different configurations of longitudinal and transverse GFRP layers were applied to improve the columns' flexural and shear capacity. The results showed a significant enhancement in the strength and stiffness of RC columns, leading to improved blast resistance. The application of transverse GFRP wraps increased the post-peak ductility of the concrete and improved the debonding strain and performance of the longitudinal GFRP. Analytical predictions, using the single-degree-of-freedom (SDOF) dynamic analysis method, closely matched the experimental results, accurately predicting maximum displacements, time to peak displacements, and residual displacements. Longitudinal GFRP-retrofitted columns exhibited reduced displacements and quicker response times, while thicker retrofits supported higher pressure-impulse combinations. Additionally, GFRP transverse jackets enhanced ductility, resistance to debonding, and helped prevent spalling by offering partial confinement. The failure of retrofitted columns was often attributed to the rupture and debonding of longitudinal GFRP layers. The study also highlighted the impact of repeated blast testing, with the most pronounced effects observed in non-retrofitted and minimally GFRP-retrofitted columns[25].

In 2016, Zhang et al. conducted a study on concrete-filled double-walled steel tubes (CFDS) and found that they outperformed RC columns under near-field blast loading. A total of seven square and four round columns were tested. Both the outer and inner steel pipes of the square and round tubes had a thickness of 5 mm, with external and internal dimensions of 210 mm and 100 mm, respectively. The tests used an emulsion explosive, equivalent to 1, 17, 35, and 50 kg of trinitrotoluene (TNT), placed 1500 mm from the columns. The results revealed that the sample without an axial load exhibited 25% greater tip displacement compared to the sample under a 1000 kN axial load. Moreover, the study indicated that the overall structural response, including the vibration period, maximum strain, and residual strain, was largely unaffected by the void area inside the column[26].

In 2016, Fouché et al. proposed modifications to seismic jacketing details to enhance the blast resistance of bridge columns. Their approach aimed to mitigate the risk of direct shear failure commonly associated with seismic retrofitting by incorporating structural steel collars at the top and bottom of the columns to better distribute shear forces. This concept, known as the Modified Steel Jacket Column (MSJC), was evaluated through blast tests, which demonstrated its effectiveness in preventing structural failure. Under extreme blast loads, most specimens exhibited satisfactory ductile behavior, with base rotations remaining within acceptable limits[27].

Numerical Studies

While experimental investigations are crucial, the role of numerical simulations in advancing the development and understanding of blast-resistant structures, particularly reinforced concrete (RC) columns, cannot be overstated. Finite Element Analysis (FEA) is one of the advanced computational techniques used in numerical studies to replicate the complex interactions between structural elements and blast waves. These simulations offer the advantage of exploring a wide range of scenarios, such as varying blast intensities, angles of incidence, and column configurations, at lower costs and under controlled conditions. By incorporating detailed material properties and structural geometries, numerical models enable the dynamic behavior of RC columns under blast loads to be thoroughly analyzed. Validating and calibrating these models using empirical data from experimental studies enhances their accuracy and reliability. This approach not only deepens our understanding of how structures withstand explosions but also strengthens their predictive capabilities. Additionally, numerical simulations allow for the evaluation of various strengthening techniques, such as steel jacketing or fiber-reinforced polymers (FRP), in a virtual environment before practical implementation. This helps designers optimize building safety by testing multiple explosion scenarios and improving resilience strategies to protect lives during such incidents[28], [29], [30].

In 2019, Li et al. investigated the behavior of Concrete Filled Double Steel Tube (CFDST) columns when subjected to short-range explosions. Four large-scale experiments were conducted on three columns, each 2.5 meters in height, with inner and outer diameters of 159 mm and 325 mm, respectively, and inner and outer steel tubes with a thickness of 6 mm. The first and second tests were carried out on the first column at safe distances of 300 mm and 200 mm, and 400 mm and 500 mm from the supporting surface. These tests aimed to evaluate the effects of varying safe distances using a 5 kg TNT explosive charge. The columns exhibited local concavities ranging from 10 mm to 80 mm, with the largest indentation corresponding to the highest TNT load in the previous test. Along with the increased concavity, the greater explosive load caused the steel tube to rupture when positioned closer to the blast. The steel tubes played a key role in preventing the concrete from crumbling and helped dissipate the energy from the explosion[31].

In 2020, Cui et al. investigated the damage response of two concrete-filled steel pipe columns subjected to near-field explosive loads, with a distance ratio of 0.14 m/kg1^11/3^33. Each column was 1800 mm in height, with the load applied 500 mm from the middle of the column's height. One column was made of solid concrete, reinforced with an external steel tube that was 7 mm thick and had a diameter of 273 mm. The second column was similar in design, but with a hollow interior and an additional internal steel tube, 3 mm thick and 50 mm in diameter. Both columns were subjected to a 50 kg TNT explosive charge. The results showed that the solid concrete column with external steel reinforcement experienced 40% less deformation at mid-height compared to the hollow concrete column with both external and internal steel tubes. Deformations at the top and bottom of the columns were similar for both, and were minimal compared to the deformations observed at mid-height[32].

In 2020, Thai et al. investigated the behaviour of 250 × 250 × 3600 mm rectangular concrete columns that had been retrofitted with steel jacketing under blast loads using a commercial FE analysis code. The columns' proportional spacing ranged from 0.10 to 0, 40 m/kg1/3. The study examined the impact of axial force and steel thickness on the sample's blowing performance. It was discovered that the explosion at medium height did not do as much damage as the explosion near the base of the column. It has not been demonstrated that thickening steel from 3 to 6 mm may effectively reduce explosive damage [19].

Conclusion and Future Work

The study emphasizes the vital importance of designing reinforced concrete (RC) columns capable of withstanding blast loads to maintain the structural integrity and safety of buildings and infrastructure. By combining experimental and numerical approaches, researchers can gain a comprehensive understanding of how RC columns respond dynamically to blast impacts. Experimental investigations offer essential empirical data on deformation, strain distribution, and failure patterns under blast conditions. This data is indispensable for the validation and calibration of numerical models, which simulate a range of blast scenarios, including varying intensities, angles of incidence, and column designs. To enhance the resilience and safety of blast-resistant reinforced concrete (RC) columns, future research could focus on several areas:

There is an urgent need to examine the long-term impact of repeated blast exposures on RC columns. Understanding these effects is crucial for creating effective maintenance and retrofitting strategies that can extend the service life of RC columns.

Perform in-depth studies on how blast loads affect different structural configurations and geometries of RC columns. This should include evaluating the performance of columns with varying cross-sectional shapes.

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