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# Development of Blast Resistant Structural System for Critical Infrastructure- A Review

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**Abstract:** In recent years, the threat of blast loading on buildings and critical infrastructure has increased significantly due to terrorist attacks, industrial explosions, accidental gas leaks, and military activities. Conventional structures are generally designed for gravity, wind, and seismic loads, but they are often inadequate to resist the extreme pressure generated during blast events. Blast loads are characterized by very high intensity and very short duration, producing severe structural damage, progressive collapse, and loss of life. Therefore, the development of blast-resistant structural systems has become an important area of research in structural engineering. This review paper presents a detailed study of previous research related to blast loading, blast wave propagation, structural response under explosion, and blast-resistant design methodologies. The paper reviews the contributions of various researchers from 1971 to 2023 who studied blast wave characteristics, reinforced concrete structures, steel buildings, stiffened plates, containment structures, and numerical simulation techniques. Various analytical and numerical tools such as ABAQUS, LS-DYNA, SAP2000, DYNAIB, and finite element methods have been discussed in detail. The review also highlights important parameters influencing blast resistance such as stand-off distance, explosive charge weight, ductility, material behavior, reinforcement detailing, energy absorption capacity, and progressive collapse mechanisms. The paper further identifies major research gaps in the existing literature, including the limited study on hybrid structural systems, lack of experimental validation, inadequate focus on sustainable blast-resistant materials, and insufficient research on critical infrastructure under combined loading conditions. Finally, the study concludes with recommendations for future research aimed at improving the safety, resilience, and performance of structures subjected to blast loading.

**Keywords:** Blast Loading, Blast Resistant Structures, Finite Element Analysis, Progressive Collapse, Critical Infrastructure, Dynamic Response, Reinforced Concrete, Steel Structures.

## I. INTRODUCTION

In the modern era, infrastructure facilities such as government buildings, bridges, airports, industrial plants, nuclear facilities, military installations, and transportation systems are increasingly vulnerable to blast and explosion-related incidents. Explosions may occur due to terrorist attacks, accidental industrial explosions, gas leakage, chemical reactions, ammunition detonation, or military warfare. Such incidents produce extremely high-pressure waves within a very short duration, leading to catastrophic structural damage and heavy loss of life and property. Blast loading differs significantly from conventional structural loads such as dead load, live load, wind load, and earthquake load. Blast loads are dynamic in nature and involve sudden application of pressure with extremely high magnitude. The blast wave generated during an explosion travel rapidly through the surrounding medium and exerts severe impulsive forces on nearby structures. The pressure generated by a blast event may exceed several times the design load considered in normal structural design practices.

Traditional structures designed according to conventional codes are generally incapable of resisting blast loads effectively because these codes primarily focus on gravity and seismic loads. When subjected to blast loading, structural members may experience excessive deformation, cracking, spalling, crushing, local failure, or complete progressive collapse. Therefore, there is a growing need to develop blast-resistant structural systems capable of absorbing and dissipating explosive energy while maintaining structural integrity. The field of blast-resistant design has evolved rapidly over the past few decades with advancements in computational mechanics, material science, and finite element analysis. Researchers have investigated various methods to improve blast resistance, including ductile detailing, energy-absorbing systems, retrofitting techniques, advanced reinforcement methods, high-performance materials, and numerical simulation approaches. This review paper focuses on the development of blast-resistant structural systems for critical infrastructure by reviewing important previous research works. The study aims to summarize the major findings of earlier investigations, identify limitations in existing research, and highlight future research opportunities in blast engineering.

## II. LITERATURE REVIEW

A number of researchers have studied the behavior of structures under blast loading and proposed various methods to improve their performance. The important findings of these studies are discussed below.

**2.2.1 The Properties of Blast Waves Obtained from an Analysis of the particle Trajectories (1971) By J. M. Dewey** made a pioneering contribution to the field of blast wave analysis by studying the detailed properties of blast waves through the observation of particle trajectories. His research was among the first to analyze the effects of spherical and hemispherical TNT (Trinitrotoluene) explosions, providing foundational insights into the nature of blast propagation and the resulting pressure fields. One of the most significant aspects of Dewey's work was his application of the Lagrangian conservation of mass equation to the expanding blast wave. By tracking the movement of individual particles in the blast flow, he was able to determine the density distribution throughout the wave front. This approach allowed for a more refined and physically accurate representation of how blast waves evolve in space and time. Assuming adiabatic flow conditions for each element of air between the shock fronts, Dewey calculated the pressure variation across the blast wave. The assumption of adiabatic expansion (i.e., no heat exchange with the surroundings) closely resembles real conditions in a fast-moving explosive event, where thermal exchanges are negligible compared to the timescale of the blast. Further, he derived temperature and sound speed within the blast wave region by utilizing the calculated pressure and density values. This was done under the assumption of a perfect gas behavior, employing the ideal gas law as the equation of state to link thermodynamic variables. This allowed for a comprehensive thermophysical description of the post-detonation gas field. Dewey's work laid the groundwork for modern blast modeling by combining physical insight with mathematical rigor, and his methodology continues to influence how researchers simulate and predict the behavior of air blasts resulting from explosive detonations. His contributions are particularly valuable for the validation of numerical codes and for the development of safety standards in blast-resistant structural design.

**2.2.2 A Review of methods for predicting bomb blast effects on buildings (2003) By Alexander M. Remennikov.** conducted an important study focused on the various methods used to predict the effects of bomb blasts on buildings, with particular attention to scenarios involving the detonation of high-explosive devices near single structures. The study recognized the critical need for accurate and reliable predictions of blast loads to ensure the safety and resilience of commercial and public buildings in the face of such extreme threats.

1. To address this challenge, Remennikov examined both simplified analytical techniques and advanced numerical methods. The simplified analytical approaches were primarily used to provide conservative estimates of the blast effects. These methods are beneficial for preliminary assessments and design considerations, offering quick insights into potential structural damage without the need for extensive computational resources. However, they may lack precision in representing complex structural behaviors, especially under high-intensity or close-range blast scenarios.
2. For more accurate and detailed predictions, the study explored a range of numerical modeling techniques. These included:
    - Lagrangian methods, where the mesh moves with the material, ideal for capturing solid mechanics and structural deformation.
    - Eulerian methods, where the mesh remains fixed while materials flow through it, suitable for modeling fluid and gas dynamics like blast waves.

- Euler-FCT (Flux-Corrected Transport) techniques, used to improve numerical stability and accuracy in modeling sharp gradients in blast wave propagation.
- ALE (Arbitrary Lagrangian-Eulerian) methods, which combine the advantages of both Lagrangian and Eulerian frameworks, allowing accurate simulations of fluid-structure interaction during blast events.
- Finite Element Modeling (FEM), a widely used approach for simulating structural responses to dynamic loading conditions, including high-speed impact and explosions.

By leveraging these computational techniques, the study emphasized the capability to simulate the complex interactions between blast waves and building structures with high precision. These methods help in understanding structural damage mechanisms, optimizing design for blast resistance, and improving protective measures for occupants and infrastructure.

**2.2.3 Blast & Progressive Collapse (Facts for Steel Buildings) (2005) By Kirk A. Marchand et al.** provided a comprehensive review of blast-resistant design principles as outlined by the American Institute of Steel Construction (AISC), specifically focusing on the application of these principles to steel buildings. Their work not only consolidates theoretical and design guidance but also draws heavily from real-world case studies involving catastrophic blast incidents, such as the Murrah Federal Building bombing in Oklahoma City and the Khobar Towers attack in Dhahran, Saudi Arabia. Through the examination of these high-profile events, Marchand and his colleagues identified critical vulnerabilities in structural systems subjected to blast loads. Their review emphasizes the importance of understanding blast wave propagation, pressure-time histories, and the progressive collapse mechanisms that can result from an initial structural failure. The study also delves into the dynamic response of steel structures, with a focus on ductility and energy absorption characteristics of steel columns and connections. It was observed that ductile detailing, particularly in columns and their connections, played a significant role in resisting blast-induced deformations and in preventing total collapse. This aspect of structural behavior under extreme loads demonstrates the inherent advantages of steel, including its ability to undergo large plastic deformations without sudden failure. Moreover, the research discusses the design and retrofit strategies for enhancing the blast resilience of existing and new steel structures. These strategies include the use of redundant load paths, robust connections, and controlled deformation mechanisms to dissipate blast energy effectively. In conclusion, the work by Kirk A. Marchand et al. bridges the gap between theoretical knowledge and practical application by analyzing real blast events and assessing the performance of steel structures under such conditions. Their findings underscore the necessity of integrating blast considerations into the early design phase of steel buildings and highlight the importance of material behavior, especially ductility, in determining a structure's blast resistance.

**2.2.4 Dynamic Behavior of Blast – Loaded Plates (2006) By A.K. Pandey et al.** carried out a comprehensive investigation into the effects of external explosions on the outer reinforced concrete (RC) shell of a typical nuclear containment structure. Given the critical safety requirements associated with nuclear facilities, the study aimed to assess the structural integrity and failure mechanisms of the containment shell when exposed to severe blast loads. To realistically simulate the behavior of the RC shell under blast loading, the researchers utilized non-linear material models capable of representing the material degradation and failure phenomena up to the ultimate limit states. These advanced models accounted for complex aspects such as cracking, crushing, and strain-rate effects in concrete, as well as yielding and strain-hardening behavior in reinforcement steel. The analytical approach developed for this study was implemented into the finite element code DYNAIB, which is specially designed for dynamic impact and blast analysis. By integrating the non-linear constitutive models into DYNAIB, the researchers were able to capture the progressive failure of the RC shell under the applied explosive loading. The results of the analysis provided valuable insights into the blast resistance capacity of the containment structure, highlighting vulnerable regions, potential failure modes, and the overall energy absorption characteristics. The study emphasized the importance of non-linear dynamic analysis for accurately predicting the structural response and ensuring the design safety of critical infrastructure like nuclear power plants in the event of a blast scenario.

**2.2.5 Blast Loading and Blast Effects on Structures – An overview (2007) By T. Ngo et al.** presented a comprehensive overview of the fundamental principles, analysis techniques, and design considerations for structures subjected to blast loading. Their research aimed to enhance the understanding of how blast loads interact with structural systems and how structures respond dynamically to such high-intensity, short-duration events. The study begins with a detailed explanation of the nature of blast waves, including the characteristics of shock fronts, peak overpressure, impulse, and time duration. This foundational knowledge is critical for engineers aiming to evaluate the vulnerability of buildings to explosive threats. T. Ngo et al. emphasized that blast loading differs significantly from conventional loads due to its extremely rapid application and high magnitude, necessitating specialized modeling and design strategies. One of the central contributions of the paper is its discussion on the dynamic response of different structural elements—such as beams, columns, slabs, and connections—under blast impact. The authors analyzed how material properties, geometry, boundary conditions, and structural configurations influence the ability of a component to resist or fail under blast-induced stress. They also highlighted the importance of ductility, energy absorption, and progressive collapse prevention as key design goals in blast-resistant construction. In terms of analysis methods, the study categorized approaches into analytical, empirical, and numerical techniques, discussing the advantages and limitations of each. Numerical simulation methods, particularly those using finite element analysis (FEA) and computational fluid dynamics (CFD), were identified as essential tools for accurately predicting structural response and optimizing protective design. Furthermore, the research is highly relevant to the design of infrastructure subjected to extreme events like bomb blasts, industrial explosions, and high-velocity impacts. It provides essential guidance for engineers and planners working on critical infrastructure, military installations, and high-risk public buildings, advocating for performance-based design that prioritizes safety, redundancy, and resilience. In summary, the work of T. Ngo et al. serves as a foundational reference in the field of blast engineering, offering a multidisciplinary approach that combines physics, material science, structural engineering, and advanced simulation to inform the design and analysis of blast-resistant structures.

**2.2.6 Dynamic Response Theory of Stiffened Plates (2007) By Khadid et al.** conducted an in-depth study on the dynamic response of fully fixed stiffened plates subjected to blast loading. The primary focus of the research was to understand how different stiffener configurations influence the structural behavior and resistance of plates under the extreme pressure conditions caused by blast waves. The study also addressed several key modeling parameters such as mesh density, the duration of the applied blast load, and the strain rate sensitivity of the material—all of which play critical roles in accurately capturing the structural response. To carry out the analysis, the researchers employed the Finite Element Method (FEM) as a robust numerical approach for simulating complex interactions between the blast load and the structural elements. Furthermore, they used the Central Difference Method for time integration to solve the nonlinear equations of motion, which arise due to the dynamic and often large deformations associated with blast loading. This explicit integration technique is particularly well-suited for high-speed dynamic problems such as blasts because it handles rapidly changing loads effectively and provides stable numerical results when small time steps are used. The study demonstrated that the configuration of stiffeners significantly affects the deformation behavior and overall stability of the plates under blast impact. Plates with optimized stiffener layouts exhibited better performance in terms of reduced displacement and improved energy absorption. Additionally, it was shown that finer mesh density enhanced the accuracy of the simulations, while appropriate consideration of strain rate sensitivity was necessary for capturing realistic material behavior under high strain-rate loading conditions.

**2.2.7 Response of structures to planer blast loads – A finite element engineering approach (2009) By T. Børvik et al.** conducted a focused study on the blast response of a closed steel container, analyzing its structural performance when subjected to internal and external explosive loading scenarios. This research is significant due to its emphasis on advanced numerical modeling techniques to overcome common limitations in conventional finite element methods, particularly when dealing with large deformations and high strain-rate phenomena caused by blast waves. A key innovation in Børvik's study is the use of meshless methods based on Lagrangian formulations. Traditional mesh-based methods often suffer from severe mesh distortion and advection errors under high-intensity blast loads, especially in regions undergoing rapid deformation. The meshless Lagrangian technique minimizes these issues by allowing the simulation to maintain accuracy during the propagation of blast waves through the structure and surrounding air domain. In terms of modeling, LS-DYNA was employed as the primary computational platform. The structural components of the steel container were represented using shell elements, enabling accurate simulation of thin-walled behavior and stress distribution during explosive loading. The study also introduced a methodology for generating inflow properties in both uncoupled and fully coupled Eulerian–Lagrangian simulations, enhancing the accuracy of blast wave interaction with structural surfaces. The coupled Eulerian–Lagrangian (CEL) approach allowed for a more realistic representation of the fluid-structure interaction (FSI) between the blast wave and the steel container, providing insights into the pressure transmission, wave reflection, and deformation mechanisms of the structure. By comparing the uncoupled and fully coupled models, the authors demonstrated that fully coupled simulations offer superior accuracy in predicting both global and local failure modes. In conclusion, Børvik's research provides a methodologically robust framework for simulating blast-loaded structures with high fidelity. The use of advanced numerical techniques such as meshless Lagrangian formulations and CEL simulations in LS-DYNA sets a benchmark for future studies, especially those focusing on blast containment, explosion-proof design, and protective structural engineering.

**2.2.8 Blast Analysis of Structures (2013) By Amol B. Unde, Dr. S. C. Potnis,** presents a comprehensive study on the dynamic response of structural elements when subjected to blast loading. The study is significant in the field of structural engineering as it highlights the limitations of conventional design approaches and emphasizes the need for advanced analytical methods to address the effects of blast loads. With the increasing risk of explosions due to both accidental and intentional causes, this research provides valuable insights into how structures behave under such extreme conditions. In this study, the authors have used finite element analysis (FEA) to simulate the behavior of structural components under blast loading. Finite element methods allow for detailed modeling of complex structural systems and enable engineers to study the interaction between blast waves and structural elements with high accuracy. By applying blast loads corresponding to different explosive charges and stand-off distances, the researchers were able to analyze how variations in blast parameters influence the structural response. The study particularly focuses on critical structural elements such as columns and foundations, which play a vital role in maintaining the stability and load-bearing capacity of a building. Columns are primary vertical load-resisting members, and any failure in columns can lead to progressive collapse of the entire structure. Similarly, foundations transfer loads from the structure to the ground, and their failure can compromise the stability of the building. The researchers observed that these elements are highly vulnerable to blast loads due to the sudden application of high pressure and the resulting dynamic forces. One of the key findings of the study is that conventional structural designs are not adequate to resist blast loads, as they are generally designed considering only static and seismic loads. Blast loads are highly dynamic and impulsive, and their effects are not accounted for in traditional design practices. As a result, structures designed without considering blast effects are more susceptible to severe damage or collapse when exposed to explosions.

**2.2.9 Numirical Analysis of Steel Building Under Blast Loading (2014) By Mohammad M,** presents an important study focusing on the response of steel structures when subjected to blast loads. While much of the earlier research has concentrated on reinforced concrete structures, this study highlights the behavior of steel buildings, which are widely used in industrial structures, high-rise buildings, and critical infrastructure due to their high strength-to-weight ratio and flexibility. The research aims to understand how steel structures perform under explosive loading conditions and how their design can be improved to enhance blast resistance. In this study, the author has used the structural analysis software SAP2000, which is a widely used tool for analyzing both static and dynamic behavior of structures. The use of SAP2000 allows for efficient numerical modeling and simulation of blast loading scenarios. The steel building model is subjected to different blast loads, and the structural response is evaluated based on various parameters such as displacement, internal forces, and demand-capacity (D/C) ratio. The D/C ratio is an important indicator used to assess whether a structural element is safe or overstressed under given loading conditions. The research emphasizes that blast loads can have a significant impact on steel structures due to their dynamic and impulsive nature. When a blast wave strikes a steel building, it induces sudden lateral forces that cause rapid deformation and vibration of structural elements. Although steel structures are generally more ductile compared to reinforced concrete structures, they can still experience excessive displacement and local failure if not properly designed for blast loads.

**2.2.10 Behavior of RCC Structural Members for Blast Analysis (2016) By Prof. C. M. Deshmukh, Dr. C. P. Pise, Digvijay Gajendra Phule [15],** The paper titled "Behavior of RCC Structural Members for Blast Analysis: A Review" published in the International Journal of Engineering Research and Application by Prof. C. M. Deshmukh, Dr. C. P. Pise, and Digvijay Gajendra Phule, provides an in-depth review of the behavior of reinforced concrete (RCC) structural members under blast loading. It highlights the unique characteristics of blast loads, including their impulsive nature, high intensity, and rapid application, which can cause severe damage to structural elements like beams, columns, slabs, and walls within milliseconds. The paper examines failure modes such as flexural and shear failures, concrete spalling, and crushing, emphasizing the critical role of dynamic responses influenced by standoff distances and explosive charge weights. It also discusses the application of numerical modeling techniques, such as finite element analysis, to simulate blast impacts and accurately capture material behavior under extreme conditions. Furthermore, the study recommends design and mitigation strategies to improve the blast resistance of RCC structures, including reinforcement detailing, advanced material usage, and retrofitting techniques. The authors underscore the need for further research into high-performance concrete, hybrid materials, and real-time structural health monitoring systems to enhance the resilience of critical infrastructure against blast events. This comprehensive review serves as a significant resource for advancing the understanding and design of blast-resistant RCC structures.

**2.2.11 Prediction of Blast Loading and Its Impact and Remedial Measures on Building (2017) By Sanjay S. Singh, V. G. Sayagavi,** presents an in-depth analytical study on the behavior of reinforced concrete (RC) frame structures under blast loading using advanced numerical modeling techniques. The study is particularly important in the field of blast-resistant design as it not only investigates the impact of blast loads on structures but also proposes remedial measures to improve structural safety and performance. In this research, the authors have developed a threedimensional (3D) reinforced concrete frame model using the finite element software ABAQUS, which is widely used for nonlinear dynamic analysis of structures. The modeling approach adopted in this study is highly advanced, as it incorporates realistic material behavior and structural response under extreme loading conditions. The RC frame is subjected to both gravity loads (dead load and live load) and lateral loads (blast loads) to evaluate its performance under combined loading conditions. This approach helps in understanding both local behavior (element-level response) and global behavior (overall structural response) of the building. A key aspect of this study is the use of the Concrete Damaged Plasticity (CDP) model to represent the behavior of concrete under blast loading. The CDP model is based on the Drucker-Prager failure criterion, which is suitable for modeling materials like concrete that exhibit nonlinear behavior under compression and tension. This model considers important characteristics such as cracking, crushing, stiffness degradation, and plastic deformation of concrete. By implementing this model in ABAQUS, the authors were able to simulate realistic damage patterns in structural elements when subjected to blast loads.

**2.2.12 Analysis and Impact of Blast Load on Structural Elements (2019) By Jainu Karthik, Dumpa Venkateswarlu, Alamanda Sai Kumar,** presents a detailed study on the behavior of reinforced concrete structural components when subjected to blast loading conditions. The study focuses particularly on critical load-bearing elements such as columns and shear walls, which play a major role in maintaining the stability and integrity of a building. With the increasing risk of explosions due to terrorist activities and industrial accidents, this research highlights the importance of understanding how individual structural elements respond under such extreme loading conditions. The authors emphasize that blast loads are highly intense, short-duration loads that act suddenly on structural elements, creating severe stress and deformation. Unlike conventional static loads, blast loads generate shock waves that result in rapid pressure increase followed by a sudden drop. This impulsive nature makes it difficult to predict structural behavior using traditional design approaches. Therefore, the study uses advanced numerical simulation techniques to accurately capture the response of structural elements under blast loading. In this research, the authors have used ABAQUS finite element software, which is a powerful tool for simulating complex structural behavior under dynamic loading conditions. The use of ABAQUS allows for detailed modeling of material properties, nonlinear behavior, and interaction between blast waves and structural components. By applying blast loads in the form of pressure-time histories, the researchers were able to simulate realistic explosion scenarios and study their effects on structural elements. The study investigates the response of reinforced concrete columns and shear walls, as these elements are critical in resisting vertical and lateral loads. The results show that columns are highly vulnerable to blast loads due to their slender geometry and load-bearing function. Failure of columns can lead to progressive collapse of the entire structure. Shear walls, on the other hand, perform better under blast loading due to their larger cross-sectional area and higher stiffness, which helps in resisting lateral forces and reducing deformation.

## III. RESEARCH GAP

Based on the detailed review of previous studies, several important research gaps have been identified in the field of blast-resistant structural systems. Most of the earlier research mainly depends on numerical simulation software such as ABAQUS, LS-DYNA, SAP2000, and other finite element analysis tools for studying structural behavior under blast loading. Although these numerical approaches provide detailed information regarding stress distribution, deformation, and failure mechanisms, there is still a lack of sufficient experimental investigations to validate the accuracy of these analytical models under actual blast conditions. Experimental studies are limited due to the high cost, safety concerns, and complexity associated with blast testing. Therefore, more experimental and field-based investigations are required to improve the reliability of numerical predictions. Another major research gap identified is the limited study on hybrid structural systems for blast-resistant applications. Most of the existing studies focus separately on reinforced concrete structures or steel structures. Very few researchers have investigated hybrid systems that combine reinforced concrete, structural steel, composite materials, and energy-absorbing layers. Such hybrid systems may offer better ductility, higher energy absorption capacity, and improved resistance against blast-induced damage. Hence, detailed investigations on composite and hybrid structural systems are necessary for developing efficient blast-resistant infrastructure.

The review also reveals inadequate research on sustainable and eco-friendly blast-resistant construction materials. Most conventional studies utilize ordinary reinforced concrete and steel materials without considering environmental sustainability. Very limited work has been carried out on the use of advanced materials such as fiber-reinforced concrete, geopolymer concrete, recycled aggregate concrete, nano-modified concrete, and other sustainable construction materials for blast-resistant applications. These materials have the potential to improve structural strength, ductility, and durability while also reducing environmental impact. Therefore, future studies should focus on the development and performance evaluation of sustainable blast-resistant materials. Another important gap is the limited research related to critical infrastructure under blast loading conditions. Most previous investigations primarily focus on residential or commercial buildings, while very little attention has been given to critical infrastructure systems such as bridges, water treatment plants, nuclear facilities, transportation hubs, elevated service reservoirs (ESR), industrial plants, and military structures. Since failure of such infrastructure can lead to severe economic loss, environmental hazards, and public safety risks, detailed blast analysis and protective design strategies for critical infrastructure are highly essential.

The literature review further indicates a lack of combined loading analysis in blast-resistant structural design. Most studies investigate blast loading independently without considering the simultaneous effects of other dynamic loads such as earthquakes, wind loads, or progressive collapse mechanisms. In practical situations, structures may experience multiple loading conditions together, which can significantly alter their structural response and failure behavior. Therefore, future research should focus on the combined effect of blast load with seismic load, wind load, and progressive collapse to achieve more realistic and reliable structural designs. In addition, insufficient attention has been given to retrofitting and strengthening techniques for existing structures subjected to blast loading. Although some studies discuss retrofit methods, detailed comparative investigations on different strengthening techniques such as FRP wrapping, steel jacketing, energy-dissipating devices, and smart damping systems are still limited. There is a need to evaluate the effectiveness, cost efficiency, and practical applicability of these retrofit methods for improving the blast resistance of old and vulnerable structures. Finally, limited research has been carried out on the integration of real-time monitoring and smart technologies in blast-resistant infrastructure. Modern technologies such as structural health monitoring systems, sensor-based warning systems, artificial intelligence, machine learning, and smart monitoring techniques have not been extensively explored in the field of blast engineering. These technologies can help in early damage detection, real-time structural assessment, and rapid emergency response after blast incidents. Therefore, future studies should focus on integrating intelligent monitoring systems with blast-resistant structural design to improve infrastructure safety and resilience.

## CONCLUSION

Blast loading is one of the most critical extreme loading conditions affecting modern infrastructure systems. Unlike conventional loads, blast loads are highly impulsive and can produce catastrophic structural damage within milliseconds. The present review paper examined major research contributions related to blast wave propagation, structural response, blast-resistant design methodologies, and advanced numerical simulation techniques. The literature review revealed that finite element analysis and computational simulation tools such as ABAQUS, LS-DYNA, DYNAIB, and SAP2000 play a major role in understanding structural behavior under blast loading. Researchers have demonstrated that factors such as ductility, stand-off distance, reinforcement detailing, energy absorption capacity, and material properties significantly influence blast resistance. The study also identified important research gaps, particularly in the areas of hybrid structural systems, sustainable blast-resistant materials, experimental validation, retrofitting techniques, and smart monitoring systems. There is a strong need for future research focused on developing economical, sustainable, and high-performance blast-resistant structural systems for critical infrastructure. Overall, this review paper provides a comprehensive understanding of existing blast engineering research and highlights future directions for improving structural safety and resilience against explosive threats.

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