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Prediction of Blast Loading and Its Impact on Buildings

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***Abstract:** A bomb explosion within or near a building can cause catastrophic damage to both the external and internal structural frames, including the collapse of walls, shattering of windows, and failure of critical life-safety systems. The resulting loss of life and injuries may arise from various causes such as direct blast effects, structural collapse, debris impact, fire, and smoke. Furthermore, these events often hinder evacuation efforts, leading to additional casualties. Catastrophes caused by gas-chemical explosions generate dynamic loads significantly exceeding the original design capacities of structures. Consequently, extensive research over the past three decades has focused on the development of structural analysis and design techniques to resist such blast loads. Notably, studies on reinforced concrete (RC) elements have improved our understanding of how structural detailing influences behavior under blast conditions. This study investigates the response of RC columns subjected to constant axial and lateral blast loads using the finite element software ANSYS. Various boundary conditions were considered, employing meshless methods to reduce mesh distortion. The analysis involved applying a constant axial force to achieve equilibrium, followed by a short-duration lateral blast load to observe dynamic response over time. A comprehensive understanding of blast phenomena and structural dynamics is essential for the effective design of structures resistant to explosions.*
***Keywords:** Bomb explosion, blast load, structural damage, reinforced concrete, RC column, ANSYS, finite element analysis, dynamic response, meshless method, structural safety.*

I. INTRODUCTION

In the past few decades, a significant amount of attention has been directed toward understanding and mitigating the effects of blast and earthquake forces on structures. Earthquake engineering, though rooted in antiquity due to the long-standing impact of seismic events on human settlements, has witnessed a major surge in research, understanding, and technological advancement primarily over the past fifty years. This era has brought with it a sophisticated understanding of seismic hazards, the development of complex models for structural response, and the integration of advanced materials and design principles aimed at enhancing the resilience of buildings and infrastructure against seismic actions. Earthquake engineering today involves not only the design of new earthquake-resistant structures but also the retrofitting and strengthening of existing ones, often in densely populated or historically vulnerable regions. The increasing availability of data from past seismic events, improved computational models, and global cooperation in research have led to new innovations in seismic design codes, damping systems, base isolators, and predictive modeling. Conversely, the phenomenon of blast loading, although not entirely new, has come to the forefront of structural engineering concern in more recent years. The evolution of blast-related research and development has largely been influenced by accidental explosions in industrial settings and, more alarmingly, by deliberate acts of terrorism and warfare. The knowledge base concerning blast effects on structural components has been greatly enriched by the concerted efforts of institutions such as the Army Corps of Engineers, the U.S. Department of Defense, the U.S. Air Force, and other governmental bodies, as well as through public and private research entities. Academic institutions, particularly the Massachusetts Institute of Technology (MIT), the University of Illinois, and several other prominent universities and engineering firms, have played a pivotal role in investigating the complexities of blast loading, structural response, energy dissipation, and failure mechanisms under high-intensity dynamic loads. The prediction of blast loading and its impact on buildings is a critical aspect of structural engineering, particularly in the context of modern infrastructure, where threats of explosions, whether due to terrorist attacks, industrial accidents, or natural events such as earthquakes, are of significant concern. As urbanization accelerates and buildings become taller and more complex, understanding how structures respond to extreme dynamic loads, such as those produced by blasts, has gained paramount importance.

A blast loading event involves rapid pressure changes, shock waves, and high-velocity air movements, all of which can lead to catastrophic damage to buildings if not adequately addressed in the design phase. The energy generated by explosions can cause severe structural deformations, compromising the integrity of building elements such as columns, beams, slabs, and connections, potentially leading to collapse.

II. LITERATURE REVIEW

A. Khadid et al. [1] 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.

A.K. Pandey et al. [2] 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.

Alexander M. Remennikov et al. [3] 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.

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.

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.

J. M. Dewey et al. [4] 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.

Kirk A. Marchand et al. [5] 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.

Ronald L. Shope et al. [6] conducted a detailed investigation into the response behavior of wide flange steel columns when subjected to a combination of constant axial load and lateral blast loading, a scenario commonly encountered in real-world structural systems exposed to explosive threats. The research specifically focused on understanding how varying slenderness ratios and boundary conditions influence the structural performance under dynamic loads. To carry out the analysis, Shope employed the finite element software ABAQUS, known for its advanced capabilities in simulating nonlinear structural behavior under complex loading. The steel columns were modeled under a non-uniform lateral blast pressure distribution, which more accurately represents real blast scenarios as opposed to uniform loads typically used in simplified models. A key aspect of the study was the variation of axial loading levels, which allowed Shope to observe changes in structural response, particularly the displacement time histories and plastic hinge formations. The results revealed that increased axial load led to a higher tendency for plastic hinges to develop at lower lateral displacements, indicating a reduction in blast resistance as axial compression increased. This highlights the critical interplay between axial forces and lateral dynamic demands during a blast event. Additionally, the study found that column slenderness ratio significantly affected the failure modes. Slender columns were more prone to global buckling, while stockier columns exhibited more localized plastic deformations and energy absorption capabilities. Boundary conditions also played a crucial role, with fixed-fixed supports offering greater resistance compared to pinned or partially restrained conditions. Overall, Ronald L. Shope's work provides valuable insights into the nonlinear dynamic behavior of steel columns under blast conditions, demonstrating the importance of considering axial loads, slenderness, and realistic boundary conditions in blast-resistant design. The findings have practical implications for improving the design, retrofitting, and risk assessment of steel-framed structures in blast-prone environments.

T. Børvik et al. [7] 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.

T. Ngo et al. [8], in their widely referenced study titled "Blast Loading and Blast Effects on Structures", 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.

Amol B. Unde et al. [9] the study titled "Blast Analysis of Structures" by Amol B. Unde and Dr. S. C. Potnis, explores the dynamic response of structural elements to blast loads. Using finite element software, the researchers simulated blast wave propagation under varying explosive charges and distances, focusing particularly on elements such as columns and foundations. Their findings revealed that conventional structural designs, which do not typically account for blast load dynamics, are highly vulnerable to explosive impacts. The study emphasized the importance of incorporating advanced analytical methods into structural design practices to enhance resilience against blast-induced damage.

Dipika Purushottam Mali et al. [10] the paper "Impact of Blast Loading on Building" by Dipika Purushottam Mali and Sachin Balkrishna Mulay, investigates the behavior of reinforced concrete (RC) structures subjected to TNT explosions. Utilizing finite element simulations, the study forecasts blast wave parameters for varying explosive charges and stand-off distances. The research underscores the necessity of understanding blast wave characteristics to develop structural designs that effectively resist such impacts. The authors advocate for the integration of computational tools to predict and mitigate blast effects, emphasizing the critical role of advanced analysis in reducing structural damage and ensuring safety.

III. PROPOSED METHODOLOGY

ANSYS is a powerful general-purpose finite element analysis (FEA) software widely used for solving a broad range of structural engineering problems, including those related to concrete and reinforced concrete (RC) structures. With its extensive element library containing over 100 different element types, ANSYS is capable of simulating the complex behavior of materials and structures under various loading conditions. In the context of modeling RC structures, ANSYS provides specific elements to accurately represent the behavior of concrete and reinforcement. For the nonlinear behavior of concrete, which is essential in capturing cracking, crushing, and other material failures, the three-dimensional solid element SOLID65 is typically used. This element is designed to handle the complex nonlinear material properties of concrete, including its ability to model both the compressive and tensile behaviors. SOLID65 is a versatile element that can capture concrete's cracking in tension and crushing in compression, making it highly suitable for simulating the response of concrete under load. For the reinforcement in RC structures, which typically consists of steel bars or mesh, the three-dimensional spar element LINK8 is employed. LINK8 is a one-dimensional element that can model the steel reinforcement in both tension and compression. It is capable of representing the material properties of steel, including its elastic and plastic behavior. The interaction between the concrete and reinforcement is crucial in accurately simulating the behavior of an RC structure under load, and LINK8 helps to model the bond between the concrete and the steel reinforcement, as well as the overall load transfer mechanism. By combining SOLID65 for concrete and LINK8 for reinforcement, ANSYS allows for a comprehensive simulation of RC structures, enabling the accurate prediction of their behavior under various loading conditions, including those that involve nonlinearities such as cracking, yielding, and plastic deformations. This capability is essential for designing and analyzing reinforced concrete structures for safety, durability, and performance under realistic conditions.

IV. RESULTS AND DISCUSSION

A. RC Column Subjected to Blast Loading

In this study, a ground floor column with a height of 6.4 meters, forming part of a multi-storey building, was analyzed to investigate the influence of different parameters on its performance under blast loading conditions (refer to Fig. 6.1). The primary variables considered in the analysis were the compressive strength of concrete and the spacing of stirrups. Specifically, two types of columns were assessed: a Normal Strength Column (NSC) with a concrete compressive strength of 40 MPa and a High Strength Column (HSC) with a strength of 80 MPa. Correspondingly, two stirrup spacing configurations were evaluated—400 mm for ordinary detailing and 100 mm for special seismic detailing.

The results indicated that an increase in concrete compressive strength allows for a reduction in the overall column size while maintaining the same axial load-bearing capacity. In this particular case, the cross-sectional dimensions of the column were effectively reduced from 500 mm × 900 mm in the NSC configuration to 350 mm × 750 mm in the HSC configuration, as summarized in Table 4.1.

Despite the reduction in size, the axial load capacities of both columns remained equivalent. Furthermore, the blast load acting on the column was calculated based on data derived from the Oklahoma City bombing report [13], with an assumed stand-off distance of 5 meters. The blast pressure profile was modeled using a simplified triangular shape (see Fig. 4.2), with the duration of the positive phase of the blast recorded at 1.3 milliseconds.

Table 4.1 Concrete grades and member size

Column	Sizes	Grade of Concrete (fck)	Stirrups Spacing	Detailing
NSC	500 × 900	40 N/mm²	400 mm	Ordinary
NSC	500 × 900	40 N/mm²	100 mm	Seismic
HSC	350 × 750	80 N/mm²	400 mm	Ordinary
HSC	350 × 750	80 N/mm²	100 mm	Seismic

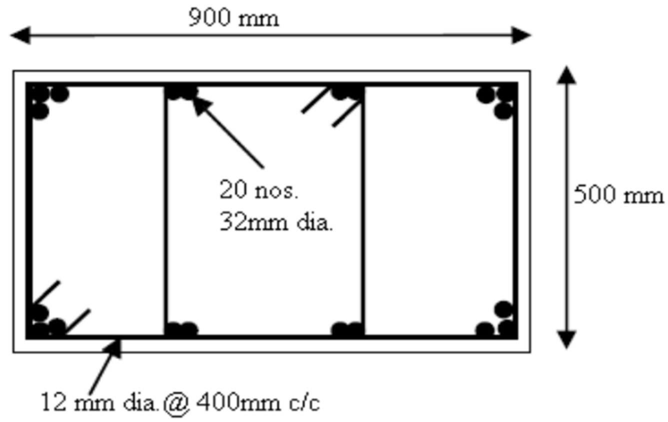

Figure.4.1: Cross section of the NSC column- ordinary detailing 400 mm stirrups spacing

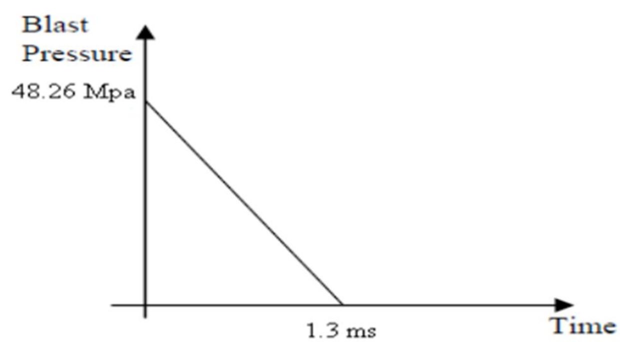

Figure.4.2: Blast Loading

The duration of the positive phase of the blast is 1.3 milliseconds, during which the structure experiences the peak overpressure that significantly affects its behavior. To accurately simulate and analyze the response of the structural component under such extreme loading, a detailed three-dimensional (3D) model of the column was developed and examined using ANSYS software. This powerful finite element analysis tool enables the incorporation of both material nonlinearity—such as plastic deformation, strain hardening, and failure—and geometric nonlinearity, which includes large deformations and post-buckling behavior, to ensure a realistic representation of the structural response. Within the dynamic analysis framework, the effects of the blast loading were rigorously modeled to reflect the transient and highly dynamic nature of the pressure wave and its interaction with the column. This comprehensive simulation approach allowed for the generation of the deflection time history, offering critical insights into how the column deforms over time in response to the blast. Such data is essential for understanding the column's structural integrity under blast loading conditions and for developing design strategies to improve resilience.

A. Problem

Determine free-field blast wave parameters for a surface burst. Procedure:
Step 1. Select point of interest on the ground relative to the charge. Determine the charge weight, and ground distance RG.
Step 2. Apply a 20% safety factor to the charge weight.
Step 3. Calculate scaled ground distance ZG:

$$Z_G = \frac{R_G}{W^{1/3}}$$

Step 4. Determine free-field blast wave parameters from Figure A 1--7 for corresponding scaled ground distance ZG:

B. Read

Peak positive incident pressure Pso
Shock front velocity Uo
Scaled unit positive incident impulse is/$W^{1/3}$
Scaled positive phrase duration to/$W^{1/3}$
Scaled arrival time tA/$W^{1/3}$
Multiply scaled values by $W^{1/3}$ to obtain absolute values.

1) Example

Required: Free-field blast wave parameters Pso, Uo, is, to, tA for a surface burst of W=1814 Kg=3990.8 lbs at a distance of Rh= 5m = 16.40ft.

2) For height h = 0 m,

Step 1: Given: Charge weight = 1814Kg = 3990.8 lb, Rh = 16.40 ft

Step 2. W = 1.20 (3990.5) = 4788.5 lbs

Step 3. For point of interest:

$$Z_G = \frac{R_G}{W^{1/3}} = \frac{16.40}{4788.5^{1/3}} = 0.973\, ft / lb^{1/3}$$

Step 4. Determine blast wave parameters from Fig.A 1--7 for

Z_G = 0.973 ft/lb1/3

P_r = 7000psi = 7 Ksi =7 x 6.895 = 48.265 Mpa

P_{so} = 850 psi = 0.880 Ksi =0.850 x 6.895 = 5.86 Mpa

$\frac{i_s}{W^{1/3}} = 16\, psi - ms / lb^{1/3}$; i_s= 16(4788.5)$^{1/3}$= 269.68 psi-ms = 1.86Mpa-ms

$\frac{i_r}{W^{1/3}} = 220\, psi - ms / lb^{1/3}$; i_r=220(4788.5)$^{1/3}$ = 3708.14psi-ms = 25.56Mpa-ms

$\frac{t_A}{W^{1/3}} = 0.08 ms / lb^{1/3}$; t_A= 0.08(4788.5)$^{1/3}$ = 1.34 ms

$\frac{t_o}{W^{1/3}} = 0.19 ms / lb^{1/3}$; t_o = 0.19 (4788.5)$^{1/3}$ = 3.2 ms

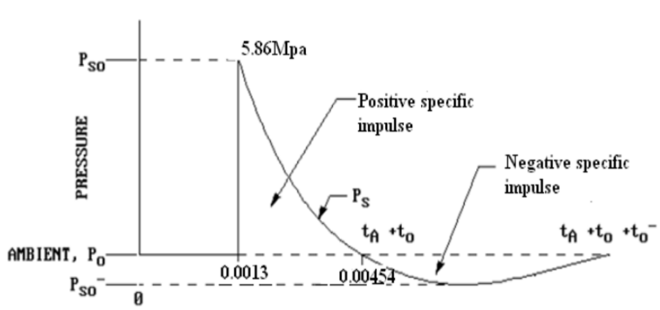

Fig.4.3: Free-field pressure –time variation for height= 0m.

3) For height h = 6.4m = 21 ft,

Solution:

Step 1: Given: Charge weight = 1814Kg = 3990.8 lb, Rh = $\sqrt{16.4^2 + 21^2}$ = 26.65 ft.

Angle of incident (α) = $\tan^{-1}\left(\frac{26.65}{16.40}\right) = 58.39^o > 45^o$

Angle of incident (α) = 45°

Step 2. W = 1.20 (3990.5) = 4788.5 lbs

Step 3. For point of interest:

$$Z_G = \frac{R_G}{W^{1/3}} = \frac{26.65}{4788.5^{1/3}} = 1.582\, ft/lb^{1/3}$$

Step 4. Determine blast wave parameters from Fig.A 1--7 for

Z_G = 1.582 ft/lb1/3

P_r = 2800psi = 2.8 Ksi = 2.8 x 6.895 = 19.306 Mpa

P_{so} = 390 psi = 0.39 Ksi = 0.39 x 6.895 = 2.690 Mpa

$\frac{i_s}{W^{1/3}} = 18 psi - ms/lb^{1/3}$; i_s= 18(4788.5)$^{1/3}$= 303.4 psi-ms = 2.10Mpa-ms

$\frac{i_r}{W^{1/3}} = 120 psi - ms/lb^{1/3}$; i_r= 120(4788.5)$^{1/3}$ = 2022.62 psi-ms = 13.95Mpa-ms

$\frac{t_A}{W^{1/3}} = 0.18 ms/lb^{1/3}$; t_A= 0.18(4788.5)$^{1/3}$ = 3.04 ms

$\frac{t_o}{W^{1/3}} = 0.4 ms/lb^{1/3}$; t_o = 0.4 (4788.5)$^{1/3}$ = 6.75 ms

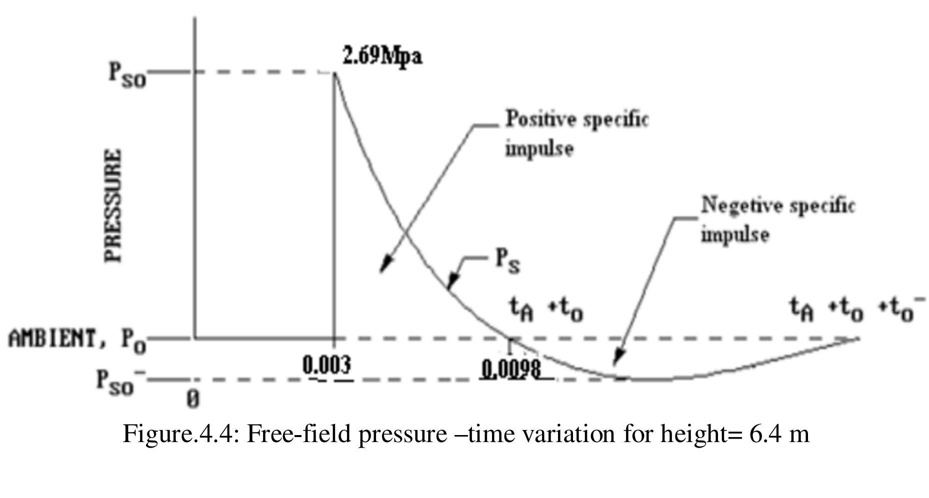

Figure.4.4: Free-field pressure –time variation for height= 6.4 m

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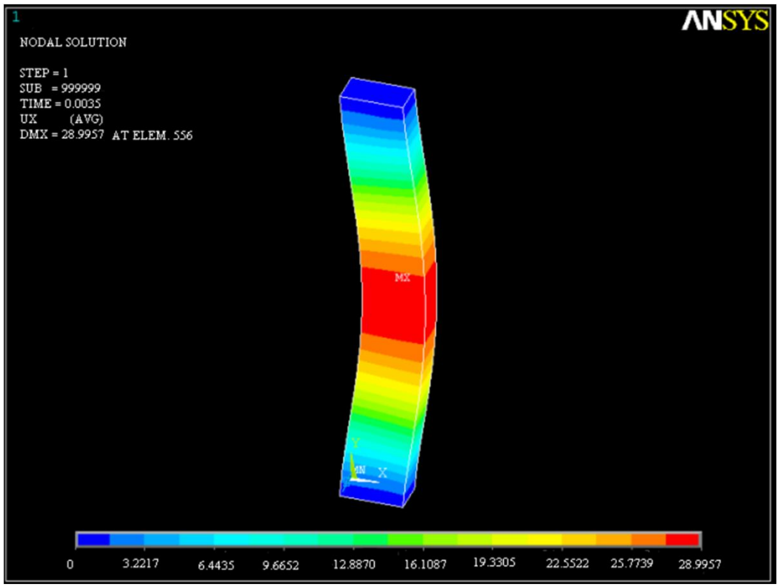

Figure.4.5: 3D model of the column using ANSYS

C. *Results*

The lateral deflection at the midpoint versus time history for two columns—one constructed with Normal Strength Concrete (NSC) and the other with High Strength Concrete (HSC)—is presented in Figures 4.6 and 4.7. These graphs provide a clear depiction of the columns' lateral resistance under blast loading conditions. From the data, it is evident that both columns experienced significant shear failure as a result of the intense, close-range bomb blast. This mode of failure indicates that the shear capacity of both NSC and HSC was exceeded under the applied dynamic loads. Interestingly, the column constructed with 80 MPa HSC, despite having a reduced cross-sectional area compared to its NSC counterpart, exhibited a noticeably higher lateral deflection. This suggests that while HSC can offer superior compressive strength, its reduced ductility and stiffness at lower cross-sectional dimensions may result in increased deformation under extreme dynamic loading. The results highlight the complex interplay between material strength, geometry, and dynamic performance, emphasizing that higher material strength alone does not necessarily equate to better blast resistance without considering other structural factors.

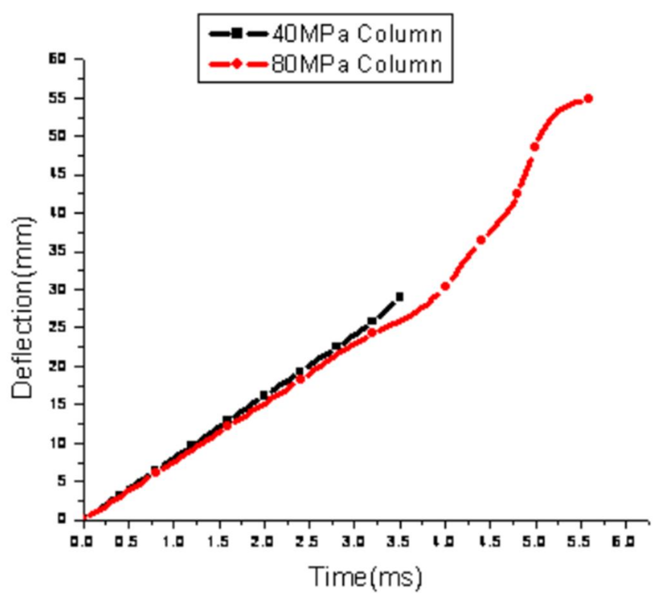

Figure.4.6: Lateral Deflection – Time history at midpoint of column with 400 mm stirrups spacing

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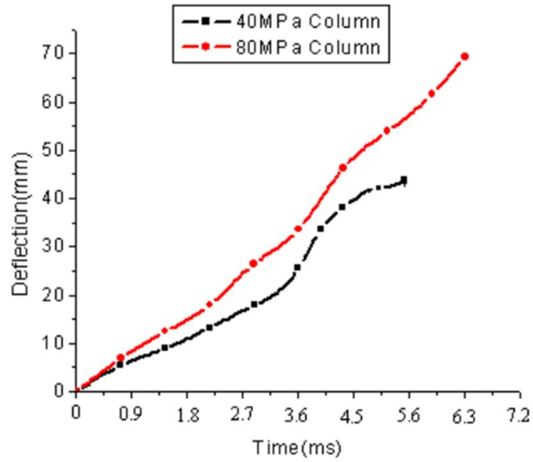

Figure.4.7: Lateral Deflection – Time history at midpoint of column with 100 mm stirrups spacing

It can be observed from Figures 4.6 and 4.7 that the effect of shear reinforcement, specifically the spacing of stirrups, plays a crucial role in enhancing the blast resistance of both High Strength Concrete (HSC) and Normal Strength Concrete (NSC) columns. The ultimate lateral displacement at failure, which reflects the ductility and energy absorption capacity of the columns, shows a notable increase with closer stirrup spacing. For the HSC column, the lateral displacement increases from 54 mm when the stirrups are spaced at 400 mm, to 69 mm with a reduced spacing of 100 mm. This clearly indicates that denser shear reinforcement allows the HSC column to accommodate more deformation before failure, thereby improving its ductility under dynamic loading conditions. A similar trend is seen in the NSC column, where the ultimate lateral displacement increases from 29 mm at 400 mm stirrup spacing to 43 mm at 100 mm spacing. These results underscore the significant contribution of closely spaced stirrups in controlling shear failure and enhancing the post-elastic performance of columns subjected to blast loads. The findings suggest that, regardless of concrete strength, shear reinforcement detailing is a key design parameter in improving structural resilience against explosive impacts.

Table 4.2 Comparison of the lateral deflection at midpoint of HSC and NSC columns

Column	Stirrups Spacing	Lateral Deflection at Midpoint (Using LSDYNA [24])	Lateral Deflection at Midpoint (Using ANSYS)
NSC	400 mm c/c	20 mm	29 mm
NSC	100 mm c/c	32 mm	43 mm
HSC	400 mm c/c	45 mm	54 mm
HSC	100 mm c/c	63 mm	69 mm

V. CONCLUSION

Based on the findings presented and supported by existing literature, the overarching goal of this study is to develop a comprehensive procedure for calculating blast loads on structural systems, including both solid-wall and framed structures, whether or not they feature openings. Additionally, the study seeks to deepen the understanding of the dynamic behavior of reinforcing steel and concrete when subjected to the high strain rates typically induced by blast events. Through the detailed analysis carried out in this phase, valuable insights were gained into the response mechanisms of reinforced concrete columns exposed to blast loads. Finite element modeling revealed that for axially loaded columns, a specific threshold of lateral blast impulse exists—exceeding this critical value leads to structural collapse before reaching the permissible beam deflection limit. Moreover, the response of columns subjected to non-uniform blast loads is significantly affected by higher-order vibration modes, particularly under asymmetrical blast conditions. When comparing normal strength concrete (NSC) columns to high strength concrete (HSC) columns, it was observed that the critical impulse required to cause failure in HSC columns is substantially higher, a result attributed to their increased stiffness and strength. Another important conclusion is that while it is difficult to shield surfaces directly facing a blast, structural resilience can still be enhanced by increasing the stand-off distance between the structure and the blast source.

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Finally, for high-risk buildings such as tall public or commercial structures, the incorporation of design measures against extreme events—including blasts and high-velocity impacts—is essential. This study strongly recommends that existing building regulations and design standards be revised to include specific guidelines for abnormal loading scenarios and progressive collapse mitigation strategies. Enhancing ductility requirements within structural design codes is also advocated, as this would improve building performance under severe dynamic loads and contribute to overall structural safety and robustness.

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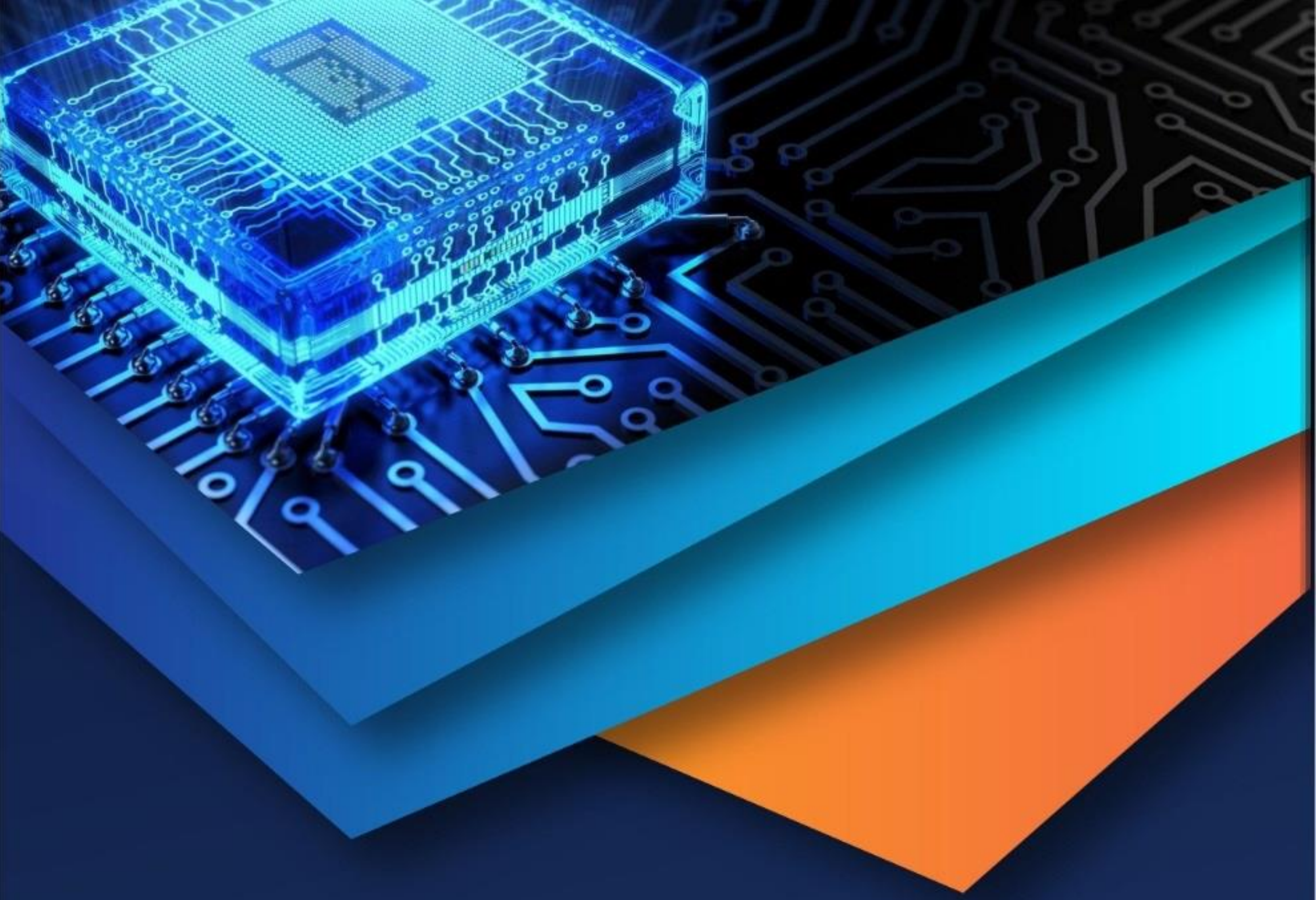

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