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Advanced 3D Simulation of Attack and Defense Dynamics in Nuclear Power Plants: Realistic Modeling of Reinforced Concrete Structure Impacts

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ABSTRACT

Understanding and accurately simulating complex physical phenomena are essential for assessing the consequences of impacts on critical infrastructures. High-fidelity 3D analysis enables the identification of structural vulnerabilities, prediction of failure modes, and evaluation of safety measures, providing critical insights to enhance system resilience. This study focuses on developing and validating high-fidelity 3D models to simulate the dynamic behavior of reinforced concrete (RC) structures under impact scenarios, with specific application to nuclear power plants (NPPs). The research utilizes benchmark examples from prior studies (Stephenson, 1977; Terranova, 2017) to represent the impact response of RC walls. A model of an RC wall with dimensions of 15 ft × 15 ft, a 12-inch thickness, and double-layered rebars was subjected to a Schedule 40 steel pipe projectile. The projectile impacted the wall at a velocity of 98 ft/s, generating realistic impact-induced forces. Simulations were conducted using the Lagrangian element formulation in LS-DYNA (LST, 2022), incorporating nonlinear material properties for concrete, steel reinforcement, and the projectile, as well as strain rate effects to capture dynamic material behavior. Different mesh sizes in the models were used and analyzed to achieve a balance between computational efficiency and result accuracy. Highly nonlinear dynamic analyses were carried out, with explicit time integration to solve for the transient response of the RC wall. Post-processed results were visualized through detailed 3D animations, offering an intuitive understanding of failure mechanisms and debris trajectories. The results were compared with experimental data to ensure model validation, showing strong agreement in the failure patterns observed on both the impact and exit sides of the RC wall. The study provides critical insights into the structural vulnerabilities of NPPs, accurately reproducing failure patterns, debris behavior, and dynamic responses under high-velocity impacts. The findings enhance safety and damage mitigation strategies by informing structural design improvements, refining failure mechanism assessments, and optimizing response protocols for critical scenarios. By leveraging high-fidelity simulations, this work strengthens the resilience and reliability of RC structures in NPPs, offering practical guidance for safeguarding critical facilities under extreme loading conditions.

1. INTRODUCTION

Nuclear power plants (NPPs) play a pivotal role in the global energy infrastructure, producing both electricity and process heat. Among the most essential components of an NPP is the containment structure,

which protects the reactor pressure vessel and provides radiation shielding in the event of structural damage. This containment structure is engineered to endure rare seismic events, extreme meteorological conditions, including strong hurricane-induced winds, as well as critical incidents such as fires, explosions, and intentional acts of terrorism. Among these threats, projectile impacts—arising from both extreme weather events and intentional attacks—represent a critical challenge to the structural integrity of reinforced concrete (RC) walls (Terranova et al., 2018). Such impacts can induce localized damage modes, including scabbing, penetration, and perforation (Esaker et al., 2023), potentially compromising reactor safety systems and exacerbating societal disruptions, as well as long-term environmental and economic challenges (Ahn et al., 2017).

In conventional practice, empirical formulas focusing on parameters such as penetration depth and wall thickness have been widely employed to estimate impact resistance. For instance, during the 1970s—when numerous nuclear power plants were designed and constructed—the most commonly adopted formulas were the Modified Petry (MP) and Modified National Defense Research Committee (NDRC) approaches (Stephenson, 1977), both derived from empirical or semi-empirical military experiments on very thick walls. Other formulas have also been utilized, including the Army Corps of Engineers (ACE), Amman and Whitney (AW), Ballistic Research Laboratory (BRL), Bechtel (B), CEA-EDF (CEA: Commissariat à l'Énergie Atomique, EDF: Électricité de France), Central Research Institute of the Electric Power Industry (CRIEPI), Chang, and Whiffen, Kar, United Kingdom Atomic Energy Authority (UKAEA) (Kennedy, 1975; DOE, 2006; Rahman et al., 2010). Although these methods have proven practical for various applications, they often lack the precision to capture the complex interplay among material properties, strain rate effects, and dynamic loading conditions. Furthermore, while experimental investigations offer valuable insights into the impact behavior of RC structures, such tests are frequently constrained by high costs and logistical challenges, limiting their scalability (Terranova, 2017). In this context, Esaker et al. (2023) compile a limited set of historical physical test data to examine concrete resistance under diverse impact conditions, including high-velocity projectile strikes. Their work identifies key damage mechanisms, evaluates the suitability of existing empirical formulas for predicting penetration depth, and underscores crucial design parameters that influence impact resistance, thereby pinpointing areas for further research.

Recently, Finite Element Analysis (FEA) is a widely adopted numerical technique for assessing the response of structural and mechanical systems under various loading conditions, including thermal and impact loads. In high-velocity impact scenarios, explicit time integration schemes are frequently utilized to accurately capture transient behaviors. Various computational approaches are available for simulating impact phenomena, including Lagrangian-based methods, Smooth Particle Hydrodynamics (SPH) (Terranova et al., 2018), Discrete Element Methods (Sawamoto et al., 1998; Morikawa et al., 1999), and K&C Finite Element and MeshFree (KC-FEMFRE) (Wu et al., 2013). Recent advancements in computational capabilities have enabled high-fidelity simulations of impact events, particularly through software tools such as ABAQUS (Khennane, 2013) and LS-DYNA, which offer advanced material modeling capabilities. For example, Terranova et al. (2018) employed both SPH and Lagrangian approaches within LS-DYNA to investigate the impact of Schedule 40 steel pipes on reinforced concrete panels, providing critical insights into localized damage mechanisms under wind-borne debris loading. Despite these advancements, challenges persist in accurately capturing complex damage evolution behavior and addressing potential convergence issues under realistic boundary conditions, underscoring the need for continued research in this domain.

This study aims to address the challenges associated with accurately simulating the dynamic behavior of reinforced concrete (RC) walls subjected to high-velocity impacts using the finite element software LS-DYNA. Specifically, it seeks to develop and validate high-fidelity three-dimensional models capable of replicating the dynamic responses and failure mechanisms of RC structures under impact loading. To achieve this, the study incorporates advanced modeling techniques, including material models and contact algorithms. Additionally, it examines how variations in mesh size and numerical formulation affect the

trade-off between computational efficiency and predictive accuracy. The developed models are validated against experimental data to ensure reliable prediction of structural vulnerabilities, debris trajectories, and failure patterns.

The remainder of this paper is structured as follows. Section 2 describes the computational framework, including the modeling methodology, material properties, and the analysis scenario. Section 3 presents the results and discussion, focusing on model validation, the evaluation of failure mechanisms, and implications for improving structural design. Finally, Section 4 summarizes the main conclusions and provides recommendations for future research.

2. COMPUTATIONAL FRAMEWORK

2.1. Modeling Methodology

The finite element modeling approach in this study employed a Lagrangian formulation within LS-DYNA where each element's deformation is tracked relative to its original configuration. This approach is well-suited for impact problems involving localized damage, large deformations, and material failure, as it allows detailed observation of stress wave propagation and internal failure mechanisms within the structure. The simulation focused on replicating the dynamic response of a reinforced concrete (RC) wall impacted by a high-velocity steel pipe, requiring careful consideration of element types, mesh resolution, material behavior, and numerical stability.

2.1.1. Type Of Elements

Concrete Wall: The reinforced concrete wall was modeled using 8-node hexahedral solid elements with a constant stress formulation (ELFORM=1), which offers computational efficiency while adequately capturing stress wave propagation and damage evolution. To accurately represent localized damage mechanisms such as spalling, scabbing, and conical plugging, a refined mesh size of 0.2 × 0.2 × 0.2 inches was applied in a 40 × 40 inch impact zone centered at the projectile's point of contact. This resolution allowed for fine stress gradient resolution and improved tracking of fracture development. Outside the impact zone, a coarser mesh of 1.125 × 1.125 × 1.125 inches was used to reduce computational effort while still preserving the wall's global stiffness and energy absorption behavior.

Reinforcement Rebars: To realistically capture the interaction between the high-velocity steel pipe pipe and internal reinforcement during penetration, rebar within the impact zone was modeled using solid elements. This enabled direct contact interaction between the pipe and the rebar, allowing for more accurate simulation of stress transfer, localized damage, and deformation of the steel during impact. Outside the impact zone, where direct contact with the pipe was not anticipated, reinforcement was modeled using Hughes-Liu beam elements with cross-section integration. This provided a computationally efficient representation of the rebar's global structural contribution while maintaining sufficient accuracy. The transition between solid and beam rebar was handled carefully to ensure mechanical continuity and smooth load transfer across the interface between the two rebar representations.

Projectile (Schedule 40 Steel Pipe): The impacting steel pipe was modeled using shell elements with the Belytschko-Tsay formulation (ELFORM=2), chosen for its efficiency in representing thin-walled structures subjected to dynamic loading. A uniform mesh size of 0.2 × 0.2 inches was applied to the pipe surface to ensure sufficient resolution for contact with the concrete wall and internal reinforcement. The shell formulation enabled efficient computation while preserving the ability to model large deformations, local buckling, and potential erosion.

2.1.2. Explicit Integration Scheme:

The simulation employed LS-DYNA's explicit time integration scheme, which is well-suited for modeling high strain-rate events like impacts and explosions. This method computes the dynamic response by

advancing the solution through very small time steps, avoiding the need for solving large systems of equations at each step, as would be required in an implicit scheme. This allows for accurate resolution of stress wave propagation, contact events, and material failure.

To ensure numerical stability, particularly in regions experiencing large deformations or element erosion, the ERODE parameter was activated via *MAT_ADD_EROSION, allowing elements to be removed from the mesh when they reached a defined failure criterion. This helped avoid instabilities related to negative volume elements and unrealistic mesh distortion.

Furthermore, the *CONTROL_TIMESTEP keyword was used with a TSSFAC (Time Step Scale Factor) of 0.6. This factor reduced the critical time step, enhancing numerical stability and convergence at the cost of increased simulation time. The conservative timestep ensured accurate tracking of failure propagation, particularly in the high-strain-rate zones near the impact location.

2.1.3. Contact Definition:

To simulate the interaction between the projectile pipe (modeled with shell elements) and the target structure—comprising both the concrete wall and embedded solid rebar elements—the study employed the CONTACT_AUTOMATIC_NODES_TO_SURFACE contact algorithm. This contact type is well-suited for impact simulations involving complex geometries and large deformations, as it automatically detects and enforces node-to-surface interactions throughout the simulation without requiring manual pairing. To improve numerical stability—particularly due to the difference in stiffness and mesh density between the shell (pipe) and the solid components (concrete and rebar)—the soft constraint formulation (SOFT=1) was activated. This formulation adjusts contact stiffness dynamically based on nodal mass and the simulation timestep, reducing the risk of instabilities, excessive penetration, or unphysical contact forces in high-speed impact scenarios.

2.2. Material Properties

2.2.1. Concrete (RC Wall)

The RC wall was modeled using the Continuous Surface Cap Model (CSCM) material model (MAT159) (Murray et al., 2007b), chosen for its capability to represent concrete under dynamic loading conditions, such as high-velocity impacts. To account for elevated strain rates, the model applies Dynamic Increase Factors (DIFs) based on the CEB formulation for compression and the Hao and Zhou formulation for tension (Dusenberry, 2010), allowing the compressive strength to exceed its nominal value of 3600 psi under dynamic loading conditions. An ERODE parameter of 1.05 was activated to remove elements once the damage parameter reached 1 and the maximum principal strain exceeded 5%, effectively capturing concrete cracking, spalling, and scabbing without causing negative volume errors. The mesh was refined to ensure accurate stress gradients, and the material model's built-in damage mechanics allowed realistic crack initiation and propagation during severe impact events.

2.2.2. Reinforcement (Steel Rebars)

Grade 60 steel rebars were modeled with the Simplified Johnson-Cook material model (MAT098) to capture their strain-rate-sensitive behavior, as large plastic deformation can occur under high-speed impacts (Banerjee et al., 2015). Each rebar, measuring 12 mm in diameter and spaced 12 inches apart in two orthogonal directions, was embedded in the concrete wall using the CONSTRAINED_LAGRANGE_IN_SOLID approach to ensure realistic composite action. Both solid and beam rebar types were tied to the surrounding concrete using this method, ensuring displacement compatibility, consistent force transfer, and full bond behavior across the entire wall. The simplified Johnson-Cook formulation provides an efficient balance between computational cost and accuracy by incorporating yield stress variation with strain rate, enabling the representation of bar yielding, hardening, and potential rupture under extreme loading scenarios.

2.2.3. Projectile (Schedule 40 Pipe)

The Schedule 40 steel pipe, serving as the projectile, was assigned a Johnson-Cook material model (MAT015) with a yield strength of approximately 73 ksi to appropriately simulate its high-strain-rate deformation (Borvik et al., 2005). Mesh discretization relied on shell elements using the Belytschko-Tsay formulation for computational efficiency, capturing bending, denting, and possible fragmentation during impact. Johnson-Cook parameters enable plastic hardening and thermal softening while incorporating strain-rate effects, making the pipe model robust against large deformations at elevated velocities.

2.2.4. Friction Parameters

Friction at the interface between the steel projectile and the concrete surface was governed by a static friction coefficient (F_S) of 0.57, derived from Rabbat et al. (1985), and a dynamic friction coefficient (F_D) of 0.4, based on Hao et al. (2013). These values allow for initial resistance to motion before sliding occurs and account for reduced friction under sustained high-speed contact. In LS-DYNA, these coefficients are implemented through an eroding contact algorithm that updates as elements erode from the concrete surface, enabling accurate simulation of both adhesion effects at impact and subsequent sliding or gouging as the projectile interacts with the wall.

2.3. Analysis Scenario

The reinforced concrete (RC) wall, with dimensions of 15 ft × 15 ft and a thickness of 12 inches, was subjected to the impact of a Schedule 40 pipe traveling at a high velocity of 98 ft/s, oriented normal to the wall surface as shown in Figure 1. The boundary conditions for the RC wall were modeled as pinned on both sides to represent constrained support. The pipe, with a diameter matching the rebar spacing of 12 inches, was assigned an initial velocity of 98 ft/s through the INITIAL_VELOCITY_GENERATION keyword. To address potential simulation failures due to excessive deformation, erosion criteria were implemented, and the CONTROL_TIMESTEP keyword was utilized to stabilize the computational time step. The mesh resolution and material models were refined to ensure an optimal balance between computational efficiency and the accurate representation of impact dynamics.

3. RESULT

3.1. Model Validation

The numerical model was validated by comparing the penetration depth and damage patterns with experimental data (Stephenson, 1977). The results demonstrated a high degree of correlation, indicating the model's reliability in capturing key response metrics such as spalling on the front face as shown in Figure 2, scabbing on the rear face, bending of reinforcement steel, and the formation of a conical plug on the rear face as shown in Figure 3. This close agreement confirms the model's capability to simulate high-velocity impacts on reinforced concrete walls and provides confidence in its use for predicting damage patterns and assessing whether perforation will occur under similar loading conditions.

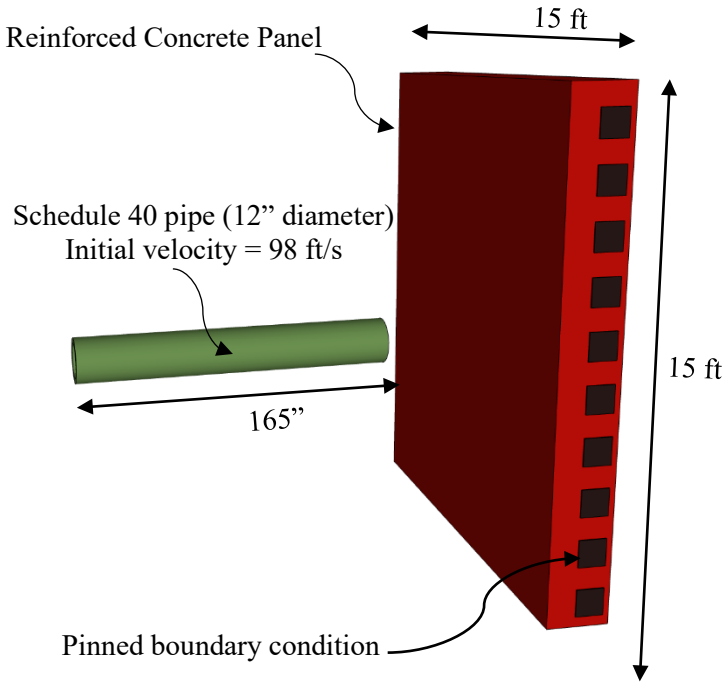
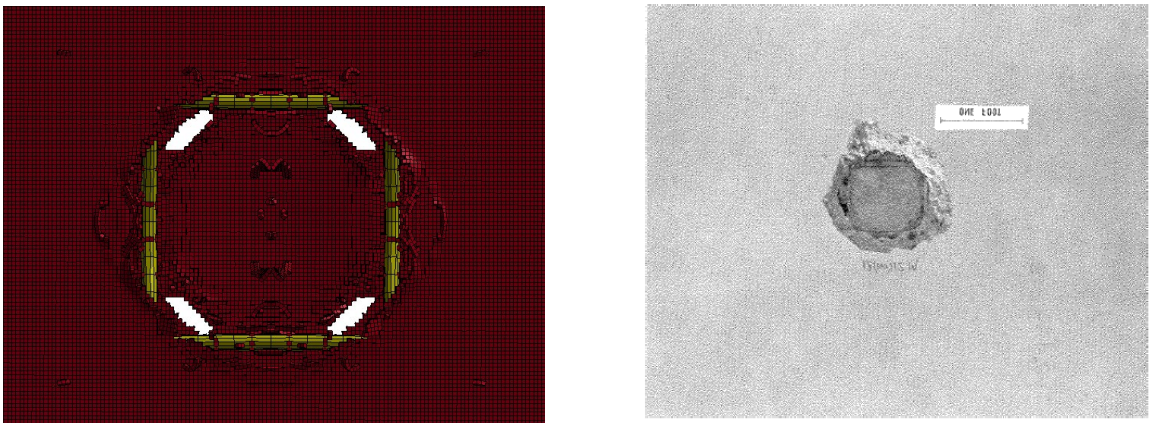


Figure 1. Schematic representation of the impact simulation framework

3.2. Damage and Failure Mechanisms

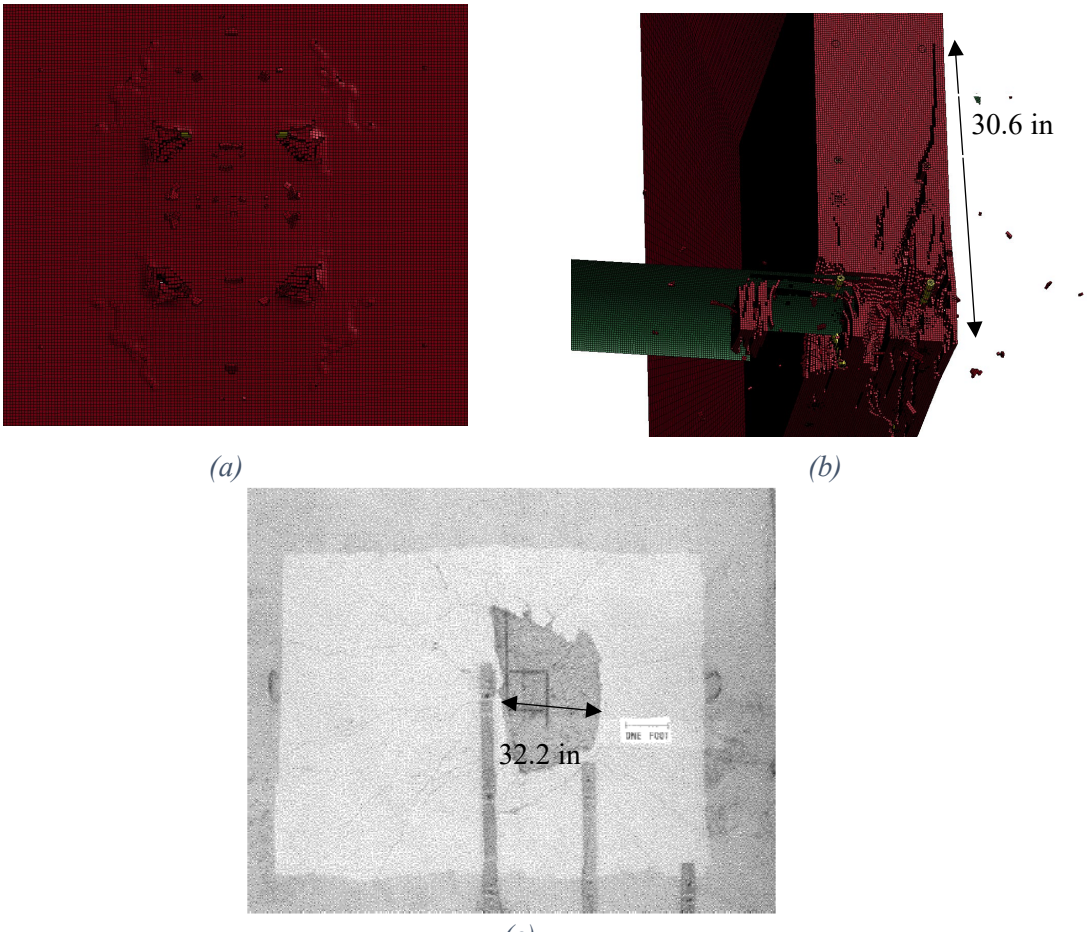
The LS-DYNA simulation successfully captured the principal damage mechanisms associated with the dynamic impact of a pipe onto a reinforced concrete (RC) wall. On the front face, localized spalling occurred due to compressive stresses exceeding the material strength at the impact site—this behavior matched experimental observations. On the rear face, the simulation showed concrete scabbing due to tensile stress reflection; however, the extent of scabbing was less severe than that observed in the experiment, where a larger breakout region was recorded. This difference may stem from limitations in modeling tensile fracture propagation or mesh resolution in the simulation. Additionally, the simulation revealed a conical fracture zone near the impact area, forming a plug with radial cracking. The predicted conical plug radius of approximately 30.6 inches was in close agreement with the 32.2-inch diameter measured experimentally, confirming the simulation’s ability to replicate shear-driven back-face failure. The pipe penetrated deeply but did not perforate the wall, a result that matches the experimental observation of penetration without perforation. Reinforcement bars inside the concrete also showed rearward bending under impact forces, further validating the force transfer and failure patterns captured by the model.

In summary, while the simulation slightly under-predicted rear-face scabbing, it accurately reproduced the critical failure mechanisms such as spalling, cone plugging, reinforcement behavior, and penetration without perforation, aligning well with the physical test outcomes and demonstrating strong predictive reliability.



(a) (b)

Figure 2. (a) Spalling damage on the front face of the RC wall captured in LS-DYNA simulation; (b) Experimentally observed spalling on the front face of the RC wall



(a) (b)

(c)

Figure 3. (a) Concrete scabbing on the rear face under surface-normal viewing in LS-DYNA; (b) Formation of a conical plug with radial cracking on the rear face in LS-DYNA; (c) Experimentally observed rear-face scabbing and conical plug formation in the reinforced concrete wall

3.3. Influence Of Mesh Density And Impact Zone Size On Conical Plug Formation

A parametric study was conducted to evaluate the influence of mesh resolution and impact zone size on the accuracy of conical plug prediction in the LS-DYNA simulation. Two concrete mesh sizes—0.4 inches and 0.2 inches—were analyzed within the impact zone, alongside two different impact zone extents: 22.5 inches and 40 inches. Results showed that the impact zone size plays a critical role in the propagation of the conical plug. The smaller 22.5-inch impact zone constrained crack development, limiting the extent of plug formation. Conversely, the 40-inch impact zone allowed the conical plug radius to expand to 30.6 inches, which closely aligns with the experimentally observed value of 32.2 inches. This suggests that an adequately large impact zone is essential to accurately capture the full progression of damage.

In terms of mesh sensitivity, under the 40-inch impact zone scenario, the coarser 0.4-inch mesh underestimated the conical plug radius, yielding a value of only 20.8 inches. In contrast, the finer 0.2-inch mesh more accurately replicated the experimental outcome, with a predicted plug radius of 30.6 inches. These findings underscore the importance of refined meshing in the impact region for accurately capturing localized failure mechanisms such as shear-induced plugging and radial fracture patterns.

3.4. Implications for Structural Design

The validated simulation framework developed in this study provides practical insights for enhancing the structural design of RC walls in critical infrastructure applications, such as nuclear power plants. By demonstrating the importance of accurate material modeling and capturing failure mechanisms such as scabbing and conical plugging, the study supports design strategies aimed at improving impact resistance. These include enhancing concrete strength, refining reinforcement detailing, and increasing wall thickness. Incorporating validated numerical tools, such as CSCM for concrete and Johnson-Cook for steel, enables engineers to simulate and optimize structural performance under extreme loading with greater confidence.

4. CONCLUSION AND FUTURE WORK

This study conducted a comprehensive investigation into the dynamic response of reinforced concrete (RC) walls subjected to high-velocity projectile impacts, with the primary goal of realistically replicating experimental results through advanced finite element modeling. The developed LS-DYNA model demonstrated strong agreement with experimental data, successfully capturing key damage mechanisms such as spalling, scabbing, reinforcement bending, and the formation of a conical plug. This validation underscores the model's reliability in simulating complex failure patterns and penetration behavior observed in real-world tests.

The analysis revealed that damage outcomes and penetration depths are highly sensitive to parameters such as material properties, boundary conditions, and numerical formulations. Parametric studies emphasized the trade-off between mesh resolution and computational efficiency, highlighting that finer meshes improve prediction accuracy at the cost of increased runtime. The use of robust material models—CSCM for concrete and Johnson-Cook for steel—was essential to achieving realistic behavior under dynamic loading conditions.

From a structural design perspective, the study also identified strategies to improve RC wall performance, including increasing concrete compressive strength, optimizing rebar layout, and enhancing wall thickness. These recommendations are particularly relevant for critical infrastructure, such as nuclear power plant containment structures, where protection against extreme physical threats is vital.

This research establishes a validated and reliable simulation framework for projectile impact on RC walls, providing valuable guidance for engineers seeking to assess and improve impact resistance in

structural systems. Future work could extend this framework to develop fragility curves or conduct probabilistic assessments, enabling more comprehensive evaluations of vulnerability and resilience for critical infrastructure exposed to extreme loading scenarios.

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