



ORIGINAL RESEARCH ARTICLE

COMPARATIVE ANALYSIS OF STRUCTURAL RESPONSE TO BLAST LOADING IN PLAIN AND REINFORCED CONCRETE WALLS

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ABSTRACT

This study presents a comparative numerical evaluation of the structural response of plain and reinforced concrete (RC) walls subjected to blast loading, with emphasis on the influence of wall geometry and reinforcement on blast resistance. Finite element simulations were conducted in ANSYS AUTODYN using a 100 kg TNT charge at a stand-off distance of 1 m. Three wall configurations, flat, L-shaped, and U-shaped, were analyzed with and without reinforcement, and their performance was assessed in terms of equivalent stress, strain, total deformation, and damage evolution. The results show that flat plain concrete walls experienced the most severe response, with peak stresses exceeding 9 MPa, strains above 13 mm/mm, large deformations of approximately 385 mm, and rapid damage progression leading to early failure. Reinforcement improved performance in all geometries; however, geometric configuration played a more dominant role in blast mitigation. Among all configurations, the U-shaped reinforced concrete wall exhibited superior performance, recording minimal peak stress (~0.3 MPa), the lowest strain response (~3 mm/mm), negligible deformation (<10 mm), and virtually zero structural damage throughout the simulation period. L-shaped walls showed moderate improvement over flat walls, with further enhancement when reinforced, but did not match the performance of the U-shaped configuration. One-way ANOVA confirmed a statistically significant difference ($F = 3.308$, $p < 0.05$) in damage reduction across wall types, leading to the rejection of the null hypothesis. The findings demonstrate that the combination of reinforcement and optimized U-shaped geometry provides the most effective blast resistance, offering critical guidance for the design of blast-resilient concrete wall systems in high-risk environments.

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1.0 Introduction

The increase in terrorist activities over the past few decades has underscored the critical need to safeguard both civilian and military infrastructure from explosive threats. Ensuring life safety requires that civil engineering structures incorporate effective protective measures capable of resisting extreme, impulsive loads generated by explosions. Reinforced concrete (RC) walls are central to this protective function, serving as primary barriers against blast-induced pressures. However, designing such walls demands a thorough understanding of their behavior under high-intensity, short-duration loading, which often cannot be adequately captured through conventional static design methods. Political, safety, and legal limitations have increasingly restricted opportunities for full-scale field blast testing, making numerical simulation an indispensable tool for examining structural response under blast loads. These simulations provide critical insights that inform practical design guidelines and improve blast-resistance strategies (Jain et al., 2015).

Several manuals form the foundation for blast-resistant structural design worldwide. The widely referenced "Structures to Resist the Effects of Accidental Explosions" (TM 5-1300, 1990) presents comprehensive

methodologies for analyzing and designing structures subjected to blast and shock effects, including detailed procedures for dynamic analysis, material response, and safety considerations for openings. Similarly, “A Manual for the Prediction of Blast and Fragment Loadings on Structures” (DOE/TIC-11268, 1992) provides guidelines for estimating loads from explosions and designing buildings to withstand them. Additional standards and manuals by Mays and Smith (1995), FEMA 426 (2003), FEMA 427 (2003), and Dusenberry (2010) further classify explosives, define protection criteria, and outline techniques for mitigating damage in public, commercial, and residential structures.

In recent years, the global uptick in violent incidents involving explosive devices, particularly in regions affected by insurgency and terrorism such as Northeast Nigeria (notably Borno State), Russia, Iran, Gaza, and Ukraine, has resulted in devastating loss of life and widespread destruction of infrastructure (Ibrahim, 2025). Many public buildings, schools, government facilities, and transportation hubs in developing regions are constructed with hollow block masonry units which fall into two basic categories: Grade A blocks with densities around 1500 kg/m³ and compressive strengths between 3.5–15 N/mm², and Grade B blocks with densities of 1100–1500 kg/m³ and compressive strengths ranging from 3.5–5 N/mm². (Ibrahim *et al.*, 2025). These strength levels are far below what is required to withstand blast loads generated by explosives with densities as high as 1.63 g/cm³. Unfortunately, conventional hollow block construction is typically designed for static gravity and lateral loads, with little or no consideration for dynamic blast pressures. This leaves many structures highly susceptible to collapse or severe damage under blast loading, a vulnerability further aggravated by substandard materials, poor workmanship, inadequate enforcement of building codes, and insufficient technical expertise in blast-resistant design (Yagob, 2007).

Despite the increasing frequency of blast-related incidents, locally contextualized research on the structural response of hollow block, plain concrete, and reinforced concrete systems under blast loading remains limited. To address this challenge, this study focuses on accessing alternative structural systems whose performance under blast loading can be quantified. By analyzing plain concrete and reinforced concrete walls. Accordingly, the objective of this study is to analyze and compare the effects of blast loads on flat concrete and reinforced concrete (RC) walls.

2. Materials

Plain concrete and RCC walls were compared to examine the effect of blast explosions. Each wall panel was 3.0 m tall, 3.0 m wide, 0.23 m thick at the top. The effect of soil structure interaction was ignored in this study, as it was considered beyond the scope. Because the same fixed-base boundary condition was applied to every model.

Materials such as concrete (M30), steel (F_y-410), TNT, and air was sourced from the ANSYS AUTODYN library. While the properties of concrete, air, and TNT are readily available in the library, the mechanical properties of reinforced concrete (RC) are not directly provided. Modeling concrete and steel separately is highly complex and demands substantial expertise. However, various researchers have addressed this challenge by proposing modified material properties that effectively replicate the behavior of reinforcing bars in concrete.

2.1 Modified Material Properties for Reinforced Concrete

The reinforced concrete was defined using equation of state (EOS), Linear polynomial This EOS is commonly used for composite materials under high strain rates because it captures compression, volumetric stiffness, and wave propagation behavior resulting from both concrete and steel.

A common polynomial form implemented in hydrocode packages is:

$$P = C_0 + C_1\mu + C_2\mu^2 + (C_3 + C_4\mu + C_5\mu^2) E \quad |$$

where

$\mu = \frac{\rho}{\rho_0} - 1$, P is pressure, ρ is current density, ρ_0 is reference density, E is internal energy per unit reference volume, and C_0, C_1, \dots, C_5 = polynomial coefficients chosen to reproduce compressive response and shock Hugoniot of the material.

2.2 Strength model Von Mises equivalent (effective) stress

The Von Mises (J_2) equivalent stress, σ_{eq} , is introduced to provide a single scalar measure of the multi-axial stress state that governs yielding in ductile materials such as steel and reinforced concrete under high strain-rate loading. In blast and impact simulations, structures are subjected to complex three-dimensional stress states; therefore, a uniaxial stress measure is insufficient to predict yielding.

The Von-Mises (J_2) equivalent stress σ_{eq} is:

$$\sigma_{eq} = \sqrt{\frac{3}{2} s_{ij} s_{ij}} = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad 2$$

where s_{ij} is the deviatoric stress tensor and $\sigma_1, \sigma_2, \sigma_3$ are principal stresses.

2.3 Yield function (Von Mises)

The yield function defines the onset of irreversible (plastic) deformation. It serves as a criterion to distinguish between elastic and plastic material behavior during dynamic loading. The yield (plasticity) condition:

$$f(\sigma_{ij}, \kappa) = \sigma_{eq} - \sigma_y(\kappa) \leq 0 \quad 3$$

where $\sigma_y(\kappa)$ is the current yield stress and κ is an internal hardening parameter (e.g., accumulated plastic strain).

2.4 Isotropic hardening law (linear hardening example)

The isotropic hardening law is required to describe how the material resists further plastic deformation after yielding. Under blast loading, materials often experience significant plastic strain, making hardening effects critical for realistic simulations. A simple isotropic hardening rule:

$$\sigma_y(\kappa) = \sigma_{y0} + H \kappa \quad 4$$

Where σ_{y0} is initial yield stress, H is hardening modulus, and κ = equivalent plastic strain (accumulated). Other hardening laws (exponential, saturation, tabulated stress-strain) may be used if calibration data exist.

2.5 Plastic flow (associative flow rule)

The plastic flow rule specifies how plastic strains develop once yielding occurs. It is required to determine the direction and magnitude of plastic deformation during each time increment. Assuming associative flow, the plastic strain rate:

$$\dot{\epsilon}_{ij}^p = \dot{\lambda} \frac{\partial f}{\partial \sigma_{ij}} = \dot{\lambda} \frac{3}{2} \frac{s_{ij}}{\sigma_{eq}} \quad 5$$

with $\dot{\lambda}$ the plastic multiplier determined from consistency conditions

2.6 Putting EOS and Strength together in an explicit hydrocode

In explicit dynamic (blast) simulations, material behavior must account for both volumetric response due to shock pressure and deviatoric response due to shear deformation. This necessitates coupling an Equation of State (EOS) with a strength model. In hydrocode explicit dynamics (blast) simulations the constitutive update typically follows:

1. Compute volumetric response using EOS to obtain pressure P .
2. Subtract hydrostatic part to obtain deviatoric stress update.
3. Apply elastic predictor: $s_{ij}^{\text{trial}} = s_{ij}^n + 2G \Delta \epsilon_{ij}^{\text{dev}}$ (where G is shear modulus).

4. Compute σ_{eq}^{trial} , if $\sigma_{eq}^{trial} > \sigma_y$, perform return mapping to yield surface and update plastic strain κ per chosen hardening law (update σ_y).
5. Update total Cauchy stress: $\sigma_{ij} = -P\delta_{ij} + s_{ij}$.

Table 1: Material properties used in ANSYS AUTODYN.

Material	Property	Value
Air	State Equation	Ideal Gas
	γ (Gamma)	1.41
	Reference Density	$1.225 \times 10^{-3} \text{ g/cm}^3$
	Reference Temperature	288.2 K
	Specific Heat (C.V.)	717.3 J/kg ·K
Reinforced Concrete	State Equation	Linear
	Reference Density	2.750 g/cm ³
	Bulk Modulus	$3.527 \times 10^7 \text{ kPa}$
	Strength Model	Von Mises
	Shear Modulus	$1.220 \times 10^7 \text{ kPa}$
	Elastic Limit	$1.000 \times 10^4 \text{ kPa}$

2.7 Technique used against Blast Loading

Strengthening existing structures using the steel reinforcement technique was an effective method to improve their resistance to blast loading and enhance overall structural integrity. This technique was more economical, easier to install, and more effective than many other retrofitting methods, particularly for TNT charges up to 100 kg. Details of the application and the resulting performance of this technique was illustrated in Figure 1.

Table 2: Significant Explosive Events Used to Establish Design Blast Load (TNT kg)

Location	TNT (kg)
U.S. Consulate, Karachi	70
U.S. Consulate, Karachi	100
Parachinar, Pakistan	50
Charbagh, Swat Valley, KPK	60
Police Checkpoint, Peshawar	80
Orakzai Agency, FATA	95
Khyber Bazaar, Peshawar	30
Timergara, Lower Dir	75
Lakki Marwat District, KPK	79
Khyber Agency, FATA	56
Ghalanai, Mohmand Agency, FATA	50

After a thorough study and analysis of terrorist activity data over the past decade, as presented in Table 2, explosive charge weights of 100 kg of TNT were selected for simulation and analysis. To strengthen the structure, steel reinforcement was fixed into the concrete. The bond between the concrete and the steel reinforcement was assumed to be rigid and fully secured by these anchors. It is noteworthy that the effect of

soil structure interaction was intentionally neglected in this study, as it will fall outside the scope of the present analysis.

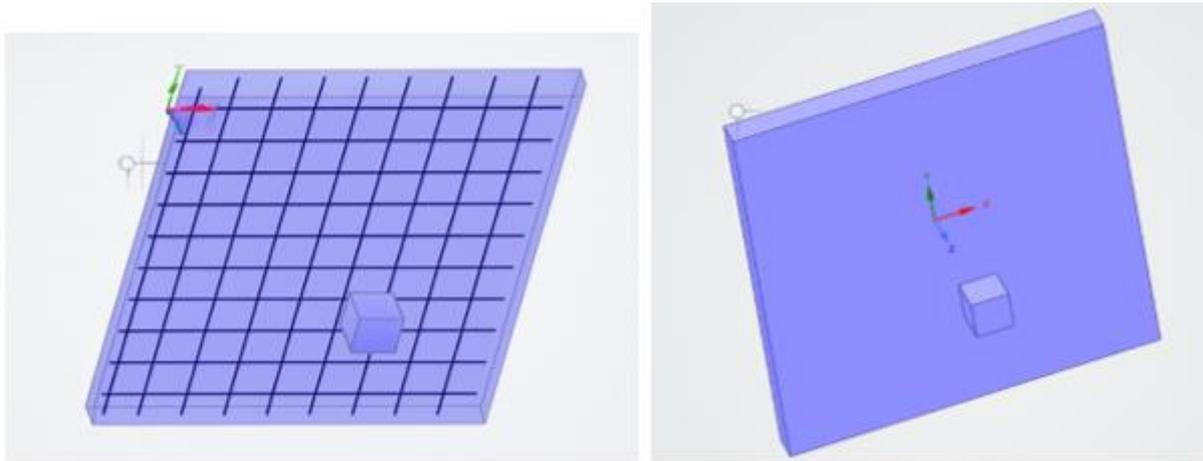


Figure 1: Plain and reinforced single concrete wall

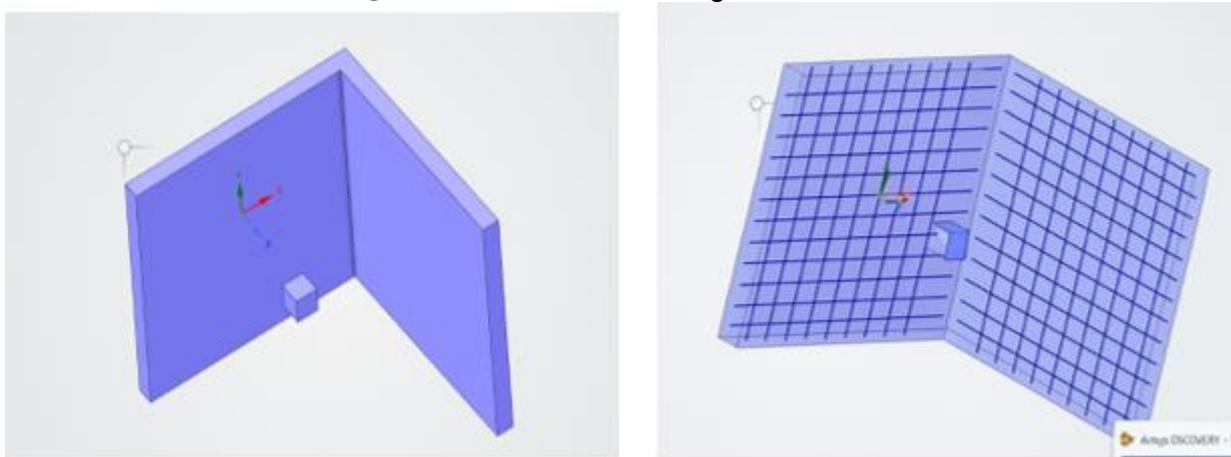


Figure 2: Plain and reinforced L-shaped concrete wall

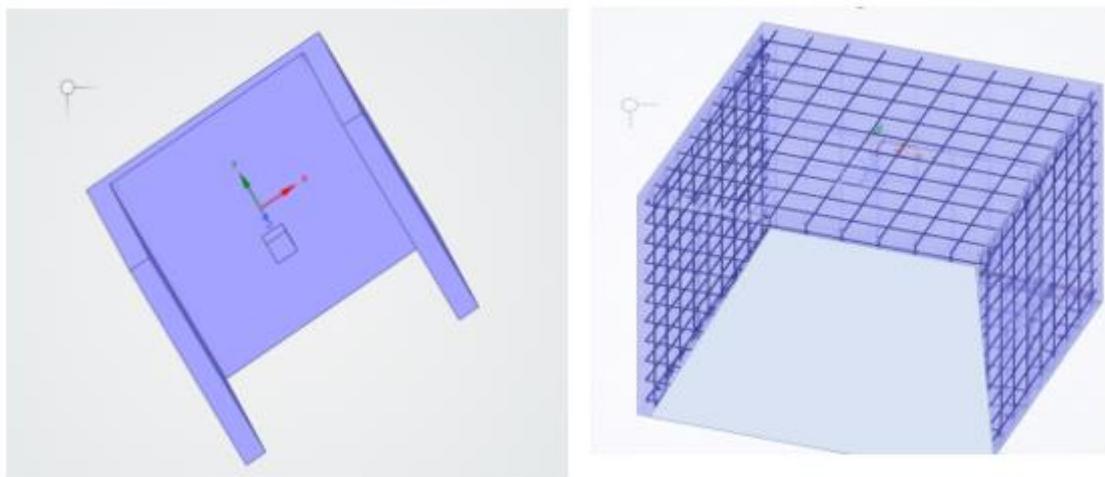


Figure 3: Plain and reinforced U-shaped concrete wall

2.8 Statistical Analysis

In this research work, data collected from the blast load simulations on various wall configuration, were analyzed using inferential statistics, such as Analysis of Variance (ANOVA), to compare the mean of structural damage among the different wall groups.

2.8.1 Null Hypothesis:

The combination of reinforcement and wall geometric design does not significantly reduce structural damage under blast loads.

3. Results and Discussion

This section presents the results obtained from blast load analysis conducted in ANSYS AUTODYN, specifically, equivalent stress, equivalent strain, total deformation, damage from blast load, and statistical analysis of ANOVA was used to test the hypothesis.

Figure 4 illustrates the equivalent stress response of various concrete wall configurations subjected to blast loading over a time period of 0.01 seconds. The plain wall without reinforcement (ES PW) and the wall with reinforcement (RW) show the highest initial peak stresses, reaching approximately 9.2 MPa and 8.6 MPa, respectively, but experience a rapid decline immediately after the peak indicating limited energy dissipation and ductility in the early phase. In contrast, the U-shaped wall with reinforcement (U-shaped R) shows a significantly lower peak stress (~ 0.3 MPa), maintaining a nearly flat profile, which suggests effective blast resistance and energy absorption through structural geometry and reinforcement.

3.1 Stress and Strain Distribution of Blast Load on Concrete Wall with and Without Reinforcement

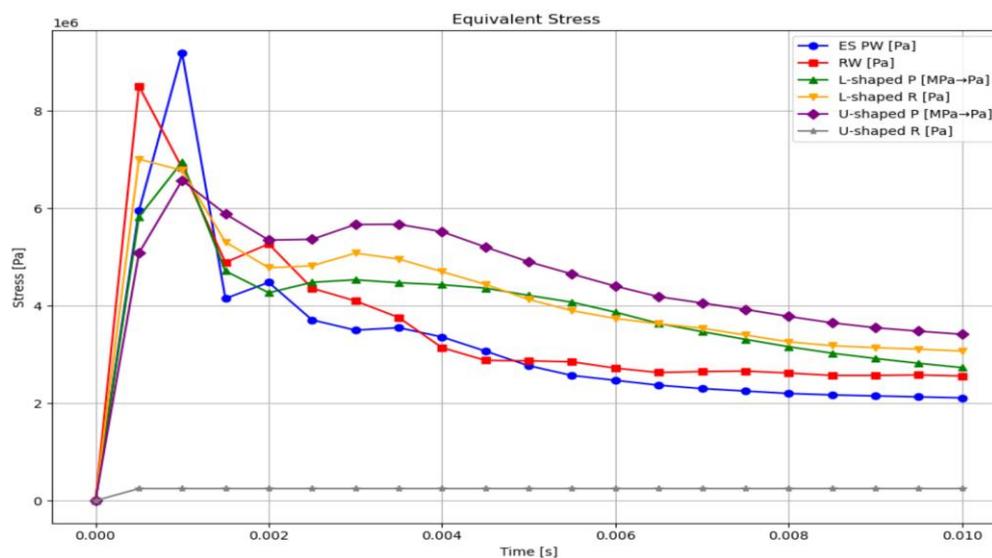


Figure 4: Equivalent elastic stress from blast load on concrete wall with and without reinforcement

The L-shaped configurations, both with and without reinforcement, demonstrate moderate peak stresses in the range of 6.5 to 7.1 MPa. Over time, the reinforced versions of both geometries (L-shaped R and U-shaped R) exhibit improved post-peak stress retention compared to their plain counterparts (L-shaped P and U-shaped P), indicating enhanced structural integrity and delayed failure progression. The U-shaped plain wall maintains the highest stress levels over the duration, suggesting it sustains loads more effectively than other unreinforced configurations, possibly due to its inherent geometric stability. This finding agrees with the study of Tiwari *et al.*, (2016) who found out in case of U-shape concrete wall, pressure time history plots clearly show the impact and pressure on concrete wall is reduced by large amount by using a 5mm thick plate.

Figure 5 depicts the dynamic strain response of various concrete wall types under blast loading over a time interval of 0.01 seconds. The data compares six configurations: plain wall without reinforcement (ES PW), reinforced wall (RW), L-shaped wall, both plain and reinforced (L-shaped P and L-shaped R), and U-shaped wall, both plain and reinforced (U-shaped P and U-shaped R). The ES PW (plain wall) exhibits the highest strain levels, peaking above 13 mm/mm, which indicates significant deformation under blast load. This is followed by the RW, which, while slightly lower at about 11.5 mm/mm, still shows substantial strain, implying that linear wall geometries, even when reinforced, are susceptible to blast-induced deformation.

In contrast, the L-shaped and U-shaped walls, especially those with reinforcement, demonstrate significantly reduced strain responses because, the applied pressure is redistributed along multiple planes instead of being resisted by a single wall face.. The L-shaped R (reinforced) and L-shaped P show intermediate strain levels around 5 to 6 mm/mm, suggesting improved stiffness and resistance to deformation due to geometric complexity and added reinforcement. More notably, U-shaped walls, particularly the U-shaped R, maintain the lowest strain levels, stabilizing around 3 to 3.5 mm/mm, indicating superior blast mitigation performance. which

aligns with the findings of Pham and Tan (2013), who demonstrated that U-shaped and other specially contoured wall geometries can effectively dissipate blast energy and reduce displacement.

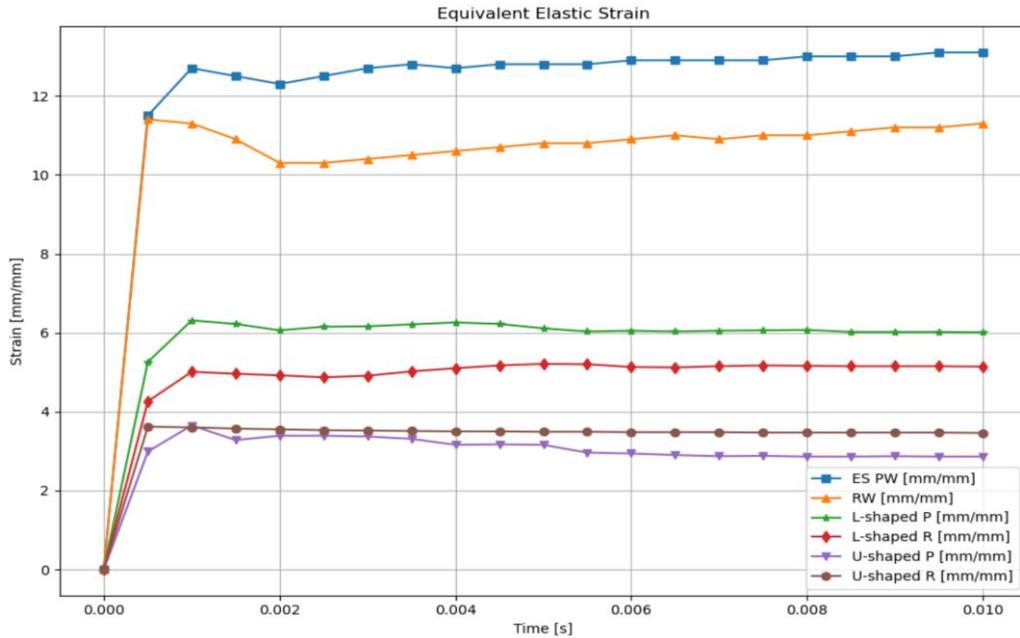


Figure 5: Equivalent Strain from Blast Load on Concrete wall with and without Reinforcement

3.1.1 Total Deformation of wall under blast load

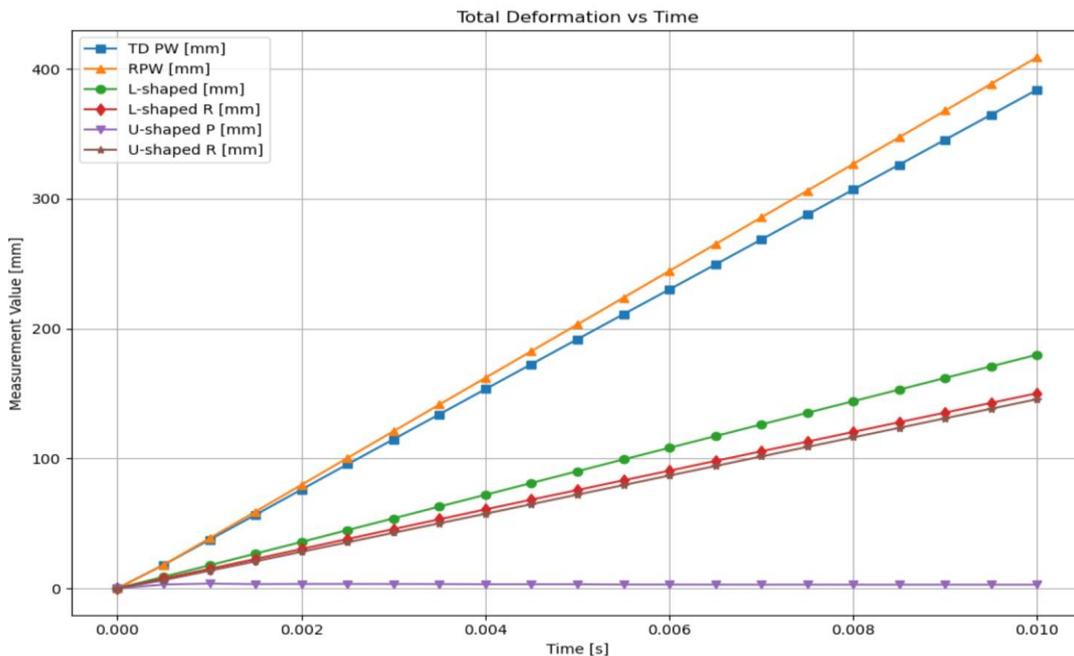


Figure 6: Total Deformation from Blast Load on Concrete wall with and without Reinforcement

Figure 6 illustrates the total deformation experienced by various concrete wall configurations under blast loading over a period of 0.01 seconds. The results clearly demonstrate that reinforcement significantly improves the structural integrity of concrete walls under blast loads. The plain wall (PW) and the reinforced wall (RW) exhibit the highest levels of deformation, with RPW reaching the maximum value of approximately 410 mm and TD PW slightly lower, around 385 mm. Interestingly, although RPW includes reinforcement, it shows more deformation than the plain wall, suggesting that the type or configuration of reinforcement in this case may not have been optimal for resisting blast-induced stresses.

In contrast, L-shaped and U-shaped configurations show a marked reduction in deformation, especially with reinforcement. The L-shaped wall without reinforcement (L-shaped P) deforms less than TD PW and RPW,

peaking around 180 mm, while the L-shaped wall with reinforcement (L-shaped R) further reduces the deformation to approximately 150 mm. Similarly, the U-shaped wall with reinforcement (U-shaped R) shows the least deformation among all configurations, staying below 10 mm throughout the time range, indicating exceptional blast resistance. The U-shaped wall without reinforcement (U-shaped P), though not as effective as its reinforced counterpart, still performs significantly better than the flat wall forms, peaking around 140 mm. The present study's result is also corroborated by Li *et al.* (2015), who found that walls with reinforced boundary elements and shaped configurations like U-forms offer better confinement, reducing crack propagation and leading to lower deformation levels under extreme dynamic loads.

3.1.2 Failure mode and damage in the wall due to blast load

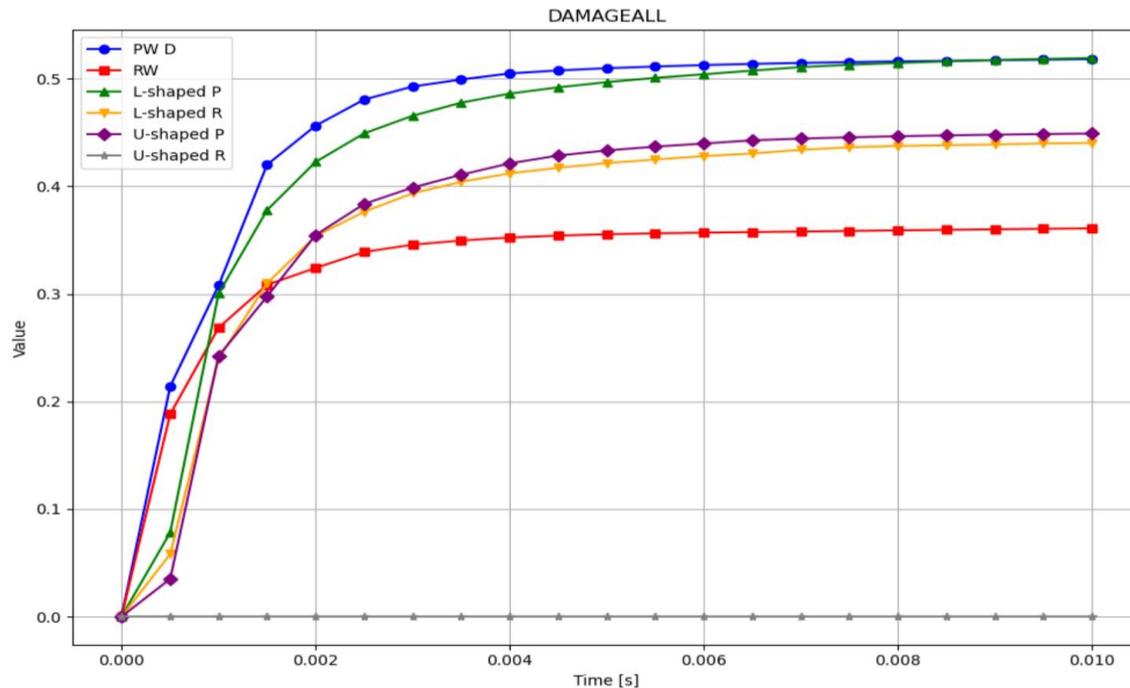


Figure 7: Damage from Blast Load on Concrete wall with and without Reinforcement

Figure 7 presents the evolution of structural damage over time for different concrete wall configurations subjected to blast loading. From the graph, the plain wall without reinforcement (PW) shows the highest level of damage, rapidly increasing to over 0.5 within the first 0.002 seconds and plateauing shortly thereafter. This indicates that unreinforced flat walls are highly vulnerable to blast loads, suffering extensive damage almost immediately.

The wall with reinforcement (RW), on the other hand, shows significantly reduced damage, stabilizing at around 0.36. This clearly reflects the beneficial effect of reinforcement in absorbing blast energy and delaying material failure. However, while reinforcement is effective, it does not completely eliminate structural damage in flat configurations.

More interesting trends emerge in the L-shaped and U-shaped wall designs. The L-shaped wall without reinforcement (L-shaped P) experiences a similar damage trajectory to PW D initially but stabilizes around 0.52, slightly better but still substantial damage. When reinforcement is added (L-shaped R), damage is reduced, leveling off at about 0.45. This suggests that geometric modification alone improves resistance, and reinforcement further enhances performance.

The U-shaped walls show a notable improvement. The unreinforced U-shaped wall (U-shaped P) demonstrates lower damage levels than its L-shaped and flat counterparts, plateauing near 0.44. The most striking result is from the U-shaped wall with reinforcement (U-shaped R), which shows virtually zero damage across the entire simulation time. This result underscores the synergistic effect of combining strategic geometry (U-shape) with reinforcement, yielding a configuration capable of withstanding high-intensity blast loads with negligible material failure. This finding is consistent with previous research that emphasizes the role of both material enhancement and structural form in resisting extreme dynamic loads. As noted by Krauthammer (2006), reinforced concrete systems demonstrate higher resistance to blast loads due to their ductility and capacity to absorb and dissipate

energy. When coupled with geometrical features like U-shaped configurations, which introduce confinement and lateral stability, the structural performance is significantly improved. According to Pham and Tan (2013), U-shaped walls are particularly effective in reducing stress concentrations and distributing blast pressures more uniformly, leading to less localized damage. Additionally, Shi et al. (2008) assert that complex wall geometries with reinforced boundary conditions perform better in blast scenarios due to improved stiffness and resistance to flexural and shear cracking.

3.1.3 Statistical analysis

Null Hypothesis:

The combination of reinforcement and wall geometric design does not significantly reduce structural damage under blast loads.

Table 3: One-way Analysis of Variance of the mean responses of the respondents on the combination of reinforcement and wall geometric design does not indicate a significant reduction in structural damage under blast loads.

	Sum of Squares	df	Mean Square	F	Sig.	Decision
Between Groups	3.236	20	.162	3.308	.741	Rejected
Within Groups	4.694	0	.049			
Total	7.930	20				

The ANOVA presented in Table 3 revealed that the $F = 3.308$, $P = 0.741$, tested at the 0.05 level of significance. Since the computed probability value is greater than the level of significance, therefore, the stated null hypothesis is rejected at the 0.05 level of significance, meaning there is a statistically significant difference in the combination of reinforcement and wall geometric design, as it significantly reduces structural damage under blast loads

4. Conclusions

- i. The study concludes that the U-shaped reinforced concrete wall offers the most efficient stress and strain distribution under blast loading, as it significantly reduces peak stress and deformation compared to flat or L-shaped walls, indicating the importance of both reinforcement and geometric configuration in enhancing structural blast resilience.
- ii. It is evident from the analysis that total deformation is lowest in the U-shaped reinforced wall, maintaining values below 10 mm throughout the blast duration, which underscores the critical role of structural geometry in conjunction with reinforcement in minimizing displacement under extreme loading.
- iii. The U-shaped reinforced wall achieved near-zero damage, clearly demonstrating that the synergy between reinforcement and curved geometry is most effective in preventing structural failure, thus establishing it as the optimal configuration for blast-resistant concrete wall systems.

U-shaped reinforced concrete walls are recommended for blast-resistant structures because their geometry and reinforcement combination provides superior stress and strain distribution under blast loading. Structural designers should prioritize wall geometry optimization alongside reinforcement detailing to effectively minimize deformation under extreme blast loads. Blast-resistant design codes should incorporate provisions that account for the beneficial effects of three-dimensional wall geometries, particularly U-shaped configurations.

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