Influence of Transverse Reinforcement Configuration and Axial Load Ratios on the Blast Resistance of RC Columns

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Abstract

Reinforced concrete (RC) columns are critical structural components in buildings and infrastructure, particularly for resisting axial and lateral loads. Under extreme loading conditions, such as blasts, their performance directly impacts structural safety and resilience. This study investigates the influence of transverse reinforcement configurations and axial load ratios on the blast resistance of RC columns through numerical simulations conducted using the LS-DYNA finite element software. Various transverse reinforcement configurations, including double square (2S), square-diamond (SD), and square-X (SX), alongside tie spacing and axial load ratios, are analyzed to evaluate their deformation and failure behavior. The Load Blast Enhance (LBE) method is used to simulate blast impacts, following UFC 3-340-02 standards. Results indicate that advanced transverse reinforcement configurations, particularly the 2S design, significantly enhance structural performance by improving stress distribution and limiting lateral deformation. Reduced tie spacing further increases stiffness and energy dissipation. Axial load ratios play a critical role; moderate levels enhance stability and energy absorption, while higher ratios reduce ductility and increase vulnerability to brittle failure. These findings provide valuable insights into optimizing reinforcement detailing and axial load considerations for the design of blast-resistant RC columns, contributing to safer and more resilient structures in high-risk environments.

Keywords: Blast Resistance, Reinforced Concrete Columns, Transverse Reinforcement Configuration, Axial Load Ratio, Blast Loading

1. Introduction

Reinforced concrete (RC) columns are vital structural elements in buildings and infrastructure, serving as primary load-bearing components and playing a fundamental role in bearing axial and lateral loads. Their performance under extreme loading conditions, such as blast events is crucial for ensuring structural stability and preventing catastrophic failures. Blast loads exert intense, short-duration, dynamic, and impulsive forces that can significantly compromise the stability of RC columns, particularly when subjected to combined axial and lateral stresses, making their behavior a critical concern for structural safety and resilience. Proper design and detailing are essential to mitigate these effects and enhance their blast resistance.

Axial load levels play a critical role in defining the blast response of reinforced concrete (RC) columns, significantly influencing their stability and failure mechanisms. Moderate axial loads enhance column performance by pre-compressing the concrete core, improving energy dissipation, and reducing lateral deformation under blast loads. This pre-compression effect strengthens the interaction between longitudinal and transverse reinforcement, delaying damage and increasing confinement. However, higher axial loads shift failure mechanisms from flexural to shear-dominated behavior, reducing ductility and increasing the likelihood of brittle failure. Shi et al. [1] demonstrated that higher axial load ratios improve moment capacity and shear strength but intensify localized spalling and crushing, particularly near the supports. Abebe and Getachew [2] observed that constant high axial loads result in more concentrated shear cracking and reduced displacement ductility, illustrating the trade-off between enhanced stiffness and increased vulnerability under excessive axial compression. Wu et al. [3] used LS-DYNA simulations validated by field tests to demonstrate that axial loads exacerbate localized damage and reduce residual axial capacity, emphasizing the importance of material strength, column details, and blast parameters. Similarly, Gholipour et al. [4] found that higher axial loads increase lateral deformation and diminish load-carrying capacity, further highlighting the trade-offs associated with excessive axial compression. Astarlioglu et al. [5] expanded on this understanding by analyzing resistance functions and pressure-impulse diagrams through single-degree-of-freedom (SDOF) and finite element methods, concluding that increased axial loads decrease structural resistance and accelerate failure under blast scenarios. These findings underscore the importance of optimizing axial load levels to balance energy dissipation and structural resilience while minimizing post-blast instability and localized damage.

Transverse reinforcement configuration plays a critical role in enhancing the blast resistance of reinforced concrete (RC) columns by improving ductility, energy dissipation, and structural stability. Closely spaced transverse ties strengthen the structural core, reducing spalling, cracking, and crushing under dynamic loads. Kwaffo et al. [6] demonstrated that reducing transverse reinforcement spacing increases the lateral resistance of RC columns, minimizing deformation and enhancing their ability to withstand extreme forces. Similarly, Zhang and Abedini [7] observed that tighter spacing preserves load-carrying capacity by mitigating localized damage after blast events. While much is understood about the effects of spacing and size, the influence of transverse reinforcement shape and layering requires further exploration.

Advanced configurations, such as rectangular, diamond, or octagonal stirrups, have shown potential to improve energy dissipation and reduce reinforcement congestion. Kim et al. [8] found that these shapes not only enhance structural performance but also optimize construction efficiency. Wu et al. [3] and Sun and Li [9] demonstrated that double-layer transverse reinforcements significantly enhance ductility and stability, particularly under cyclic or combined axial and blast loads. These studies highlight the importance of reinforcement shapes and layering in resisting lateral forces, preventing damage, and ensuring structural integrity under dynamic conditions

Further insights into transverse reinforcement configurations were provided by Anas et al. [10], who investigated single-layer versus double-layer confinement in square RC columns under close-in blast loading. Their study demonstrated that double-layer reinforcement, featuring varied shapes such as square outer stirrups with diamond or circular inner stirrups, enhanced damage resistance and reduced cracking compared to single-layer configurations. These findings emphasize the potential of advanced reinforcement shapes and layering to improve stress distribution, reduce spalling, and minimize core damage.

Additionally, the axial load ratio (ALR) influences the effectiveness of transverse reinforcement. Moderate axial loads enhance stability by pre-compressing the concrete core, improving the interaction between reinforcement layers and reducing lateral deformation. However, higher axial loads can lead to brittle failures due to reduced ductility and increased internal stress. By investigating how transverse reinforcement shapes and layering interact with varying ALRs, this research aims to develop optimized detailing strategies for RC columns, providing safer and more resilient designs capable of withstanding extreme dynamic loads.

The combined effects of transverse reinforcement shape and layering, along with varying axial load ratios, play a pivotal role in determining the blast resistance of RC columns. This study leverages numerical simulations to evaluate how these parameters influence the structural behavior of RC columns under blast loads. By focusing on advanced reinforcement configurations and their interplay with axial loads, the research provides actionable insights for developing optimized detailing strategies that enhance energy dissipation, reduce lateral deformation, and improve structural resilience. These findings are expected to contribute to the development of safer and more resilient structures capable of withstanding extreme dynamic forces, advancing design guidelines for critical infrastructure in high-risk environments.

2. Blast phenomenon

The study of blast waves is essential for understanding the impact of explosions on structural elements, particularly reinforced concrete (RC) columns. A blast wave results from a rapid energy release, forming high-pressure shock fronts that propagate outward. The pressure-time history of a blast wave is defined by a sudden rise to the peak overpressure (P_{so}) at the arrival time t_A, followed by an exponential decay during the positive phase duration (t_o). Fig. 1 illustrates the pressure-time history of a typical blast wave, showing the rapid rise and exponential decay of the positive phase, followed by the longer-duration negative phase where pressures fall below ambient levels. The Friedlander equation [11] is commonly used to model this behavior, given as (1):

$$P(t) = P_{so}\left(1-\frac{t}{t_0}\right)e^{-b\frac{t}{t_0}} \quad (1)$$

where $P(t)$ is the overpressure at time t, b is the decay coefficient, P_{so} is the peak overpressure, and t_o is the duration of the positive phase. After the positive phase, the pressure enters a negative phase, where it falls below ambient levels, inducing suction forces. However, this phase has a negligible impact on rigid structures due to its lower magnitude, with the positive phase being the dominant factor in structural response analysis [12].

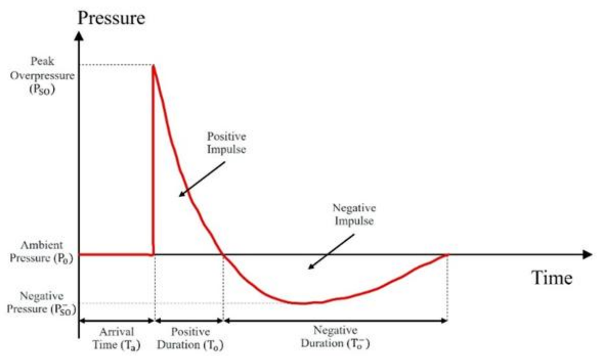

Fig. 1 Pressure-time history for Ideal blast wave.

The Hopkinson-Cranz scaling law [12] is commonly used to relate the effects of explosions to a dimensionless parameter, the scaled distance (Z), defined as (2):

$$Z = \frac{R}{W^{1/3}} \quad (2)$$

where R is the distance from the blast center, and W is the equivalent charge weight. The peak overpressure and impulse decrease with scaled distance, making this parameter critical for predicting structural damage. Wu et al. [3] demonstrated the importance of impulse, which quantifies the total force applied over time, in determining the residual capacity of RC columns after blast events.

In the study of constant and variable axial loads during blast scenarios, Abebe and Getachew [2] discovered that while constant loads led to more severe, concentrated failures like shear cracking, variable loads produced slower progressive damage with higher displacement ductility. Experimental research by Li et al. [13] on the impact of charge weight and standoff distance on residual axial capacity revealed that axial loads have a major impact on localized damage, such as crushing and spalling. Zhang et al. [14] support these findings by stressing the significance of cross-sectional geometry, reinforcement ratios, and material properties in determining residual capacity.

3. Finite element modeling of RC columns under blast loading

3.1 RC column modelling

In this study, reinforced concrete (RC) columns with a cross-sectional dimension of 300 × 300 mm and a height of 3,000 mm are investigated. The transverse reinforcement spacing of columns is 150 mm with 25 mm of covering. The dynamic behavior of these RC columns under blast and axial compression loads is simulated using the finite element software ANSYS/LS-DYNA. The Axial Load Ratio (ALR), defined as the ratio of the applied axial load to the column’s load-carrying capacity. The column's base is fixed, while the top is constrained to prevent lateral displacements. Figure 2 illustrates the details of transverse reinforcement shape of column cross-section, which include 8 bars of 20 mm diameter longitudinal bars. The study considers two axial load ratios: 0.10 for lower ALR and 0.20 for higher ALR varying three configurations of transverse reinforcement: double layer of square transverse reinforcement (2S), square outer plus diamond inner of transverse reinforcement, and square outer plus X inner of transverse reinforcement.

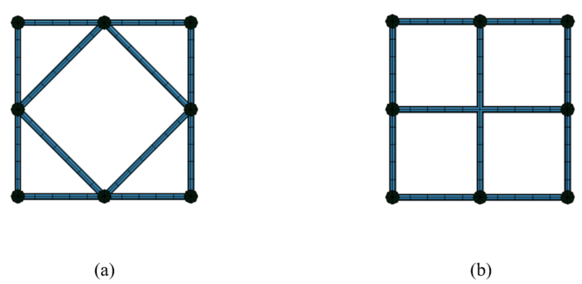

Fig. 2 Transverse reinforcement configurations: (a) Square-Diamond (SD), (b) Square-X (SX)

The concrete has an unconfined compressive strength of 42.5 MPa, a mass density of 2.4 × 10-3 g/mm3, a maximum aggregate size of 19 mm, and an erosion damage parameter of 1.05. The mass density of the reinforcement is 7.85 × 10-3 g/mm3, with a tangent modulus of 200 MPa and a Poisson's ratio of 0.3. Steel grade SR24 and SD40 standard are used for transverse and longitudinal reinforcement, respectively, with 200,000 MPa of

Young's modulus. Transverse reinforcement has a yield tensile stress of 235.4 MPa. For longitudinal reinforcement has a yield tensile stress of 392.3 MPa.

3.2 Material model

The 8-node box solid element is used to discretize the concrete. To precisely capture the localized damage modes of the column [15], the concrete and reinforcement mesh sizes are both set at 25 mm, matching the concrete covering. The solid element assignment uses the MAT_159_CSCM_CONCRETE material model, which is intended for blast and impact loading scenarios. User-defined variables can be used to modify the behavior of this material.

A formulation of truss elements was used to model both longitudinal and transverse reinforcing steel bars. Tensile or compressive stresses are applied to reinforcing steel. The element formulation key and the diameter of the reinforcement for both longitudinal and transverse rebar are necessary input variables for the SECTION_BEAM. The MAT_024_PIECEWISE_LINEAR_PLASTICITY model is an elastoplastic material model that enables the characterization of post-yield behavior by defining an arbitrary stress-strain curve based on up to eight plastic strain points and associated yield stress values.

The TNT charge mass and stand-off distance are the same in all simulations, at 20 kg and 1.5 meters (Z = 0.553 m/kg1/3), respectively. The LOAD_BLAST_ENHANCED (LBE) function is used to simulate the blast loading on RC columns. The LOAD_BLAST, LOAD_BLAST_ENHANCED (LBE), or multi-material Arbitrary Lagrangian Eulerian (MMALE) formulations can be used to model blast loading in LS-DYNA. Based on the semi-empirical Conventional Weapons Effects Program (CONWEP), the LBE keycard produces a blast load. The LBE is more computationally efficient and requires fewer input parameters than the detailed multi-material Arbitrary Lagrangian Eulerian (MMALE) method.

3.3 Model validation

The behavior of columns is examined including the axial load level, the transverse reinforcement shape, the transverse reinforcement layer, and the transverse reinforcement spacing. First, the blasting pressure that is currently employed in the finite element models is confirmed. An important source of empirical data for blast calculations, UFC 3-340-02 (formerly TM 5-1300), is compared to the results of this study. Figure 3 illustrates that there is good agreement between the numerical results and UFC 3-340-02 guidelines, as both data sets show a similar trend of decreasing pressure with increasing scaled distance.

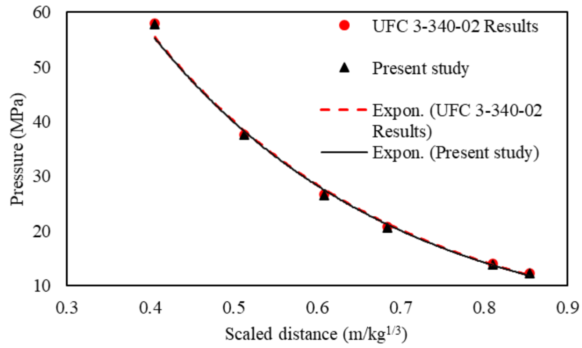

Fig. 3 Comparison of blast pressure between UFC standard and LS-DYNA numerical results.

As part of the experiment program by Siba, RC columns with 300 mm × 300 mm × 3200 mm. Each column was reinforced with four 25.2 mm bars of longitudinal reinforcement and 11.3 mm of transverse reinforcement with 300 mm of transverse reinforcement spacing. The concrete cover of the concrete column measured 40 mm. The average compressive strength of the concrete after 28 days was 41.3 MPa. Along with the blast load parameter, there was also a 123 kg TNT set 1 m above the ground with a 2.66 m standoff distance. The axial load ratio of CONV-10 is 0.32. The maximum experimental displacement measured by the authors was 39.3 mm. The displacement time history of the column with the maximum experimental displacement recorded at a height of 1 m is shown in Figure 4. A maximum displacement of 42.6 mm was recorded by the FE model.

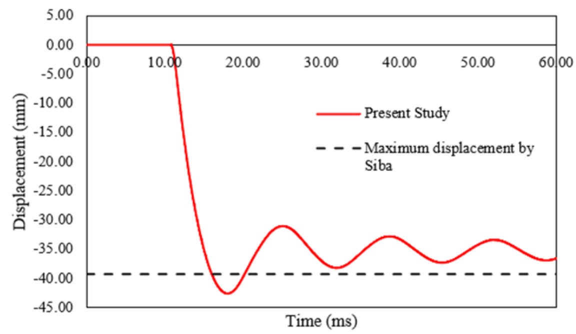

Fig. 4 Comparison of displacement time history between FE model and experimental for CONV-10.

4. Results and discussion

4.1 Effect of axial load ratios (ALRs)

The displacement time history in Figure 5 highlights the response of RC columns under varying axial load ratios (ALRs). The black line represents the response of the column with an ALR of 0.05 (8DB20 @150 mm, transverse reinforcement size = 9 mm), serving as the baseline for comparison. The results show that as the ALR increases (from 0.05 to 0.2), the maximum displacement decreases significantly. Columns with higher ALRs exhibit reduced lateral deformation due to the stabilizing effect of axial compression, which pre-compresses the concrete core and enhances stiffness. Conversely, the column with the lowest ALR (0.05) experiences the greatest displacement, indicating less resistance to blast-induced forces.

The results demonstrate a clear relationship between axial load levels and the blast performance of RC columns. Lower ALRs, such as 0.05, provide less pre-compression to the concrete core, resulting in higher displacement and more widespread damage. This behavior is indicative of a flexural-dominated failure mechanism, where the lack of axial restraint allows greater lateral deformation. As the ALR increases, the improved confinement provided by the axial compression enhances stiffness and stability, reducing displacement and concentrating damage near the blast-facing side. These observations align with findings from Shi et al. [1], which showed that moderate axial loads improve moment capacity and shear strength while reducing lateral displacement.

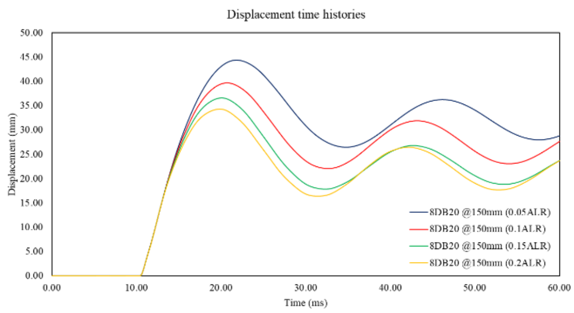

Fig. 5 Displacement time history of varying axial load ratio.

The failure modes depicted in Figure 6 (isometric and side views) further illustrate the impact of ALRs on structural behavior. The contour values, ranging from 0 to 1, indicate the stress state of the concrete, from elastic to elastic-plastic ranges. The concrete enters a softening state if the effective plastic strain exceeds a value of 1 [15]. For columns with lower ALRs (e.g., 0.05 and 0.1), extensive cracking and spalling are observed, particularly near the mid-span and blast back sides. As the ALR increases to 0.15 and 0.2, the cracking becomes more localized and less severe, with a shift in failure patterns from flexural-dominated to shear-dominated behavior. Columns with the highest ALR (0.2) show limited cracking and minimal spalling, reflecting improved structural integrity under blast loads.

However, it is important to note the trade-offs associated with increasing ALRs. While higher axial loads enhance resistance to lateral deformation, they can also increase localized stress concentrations, leading to a brittle shear-dominated failure. This balance highlights the critical need to optimize axial load levels in conjunction with reinforcement detailing to achieve both ductility and stability. The findings reinforce the importance of considering ALRs in the design of blast-resistant RC columns, providing valuable insights into tailoring reinforcement configurations for enhanced resilience under extreme loading conditions.

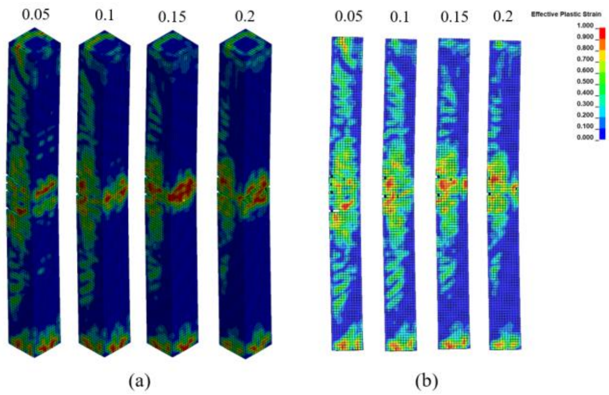

Fig. 6 Effective plastic strain of RC column varying axial load ratio.

4.2 Effect of transverse reinforcement layer

The displacement time history in Figure 7 highlights the dynamic response of RC columns under blast loading with varying transverse reinforcement configurations and tie spacing. The highest displacement is observed in the normal configuration, 8DB20 @150 mm (0.2ALR), which serves as the baseline. Following this, the advanced configurations show reduced displacement in the order of SX @150 mm, SD @150 mm, and 2S @150 mm, with the 2S configuration exhibiting the lowest displacement. When the tie spacing is reduced to 75 mm, similar trends are observed, with 2S @75 mm achieving the lowest displacement, followed by SD @75 mm and SX @75 mm.

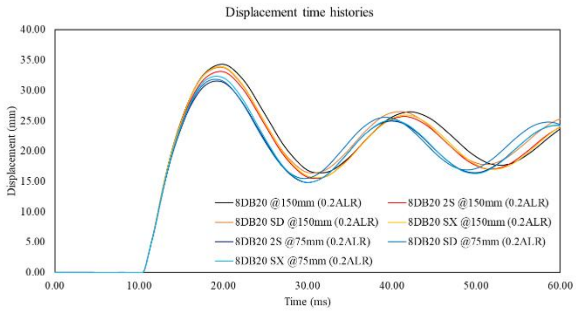

Fig. 7 Displacement time history of varying transverse reinforcement spacing and shape.

The normal configuration, 8DB20 @150 mm (0.2ALR), demonstrates the highest displacement among all configurations. This highlights the limited confinement provided by standard single-layer transverse reinforcement under dynamic blast loads. The absence of advanced shapes or layering results in insufficient energy dissipation and greater lateral deformation.

Reducing the tie spacing from 150 mm to 75 mm results in marginal improvements in displacement across all configurations. While closer tie spacing enhances confinement to some extent, its effect is minor compared to the impact of advanced reinforcement shapes and layering. This suggests that optimizing transverse reinforcement configurations, such as adopting double layers or advanced shapes, is more critical for improving blast resistance than solely relying on tighter tie spacing.

The study demonstrates that both transverse reinforcement configurations and tie spacing significantly influence the structural performance of RC columns under blast loads. The 2S configuration consistently provides superior results by enhancing structural stability, improving stress distribution, and reducing lateral deformation. However, reducing tie spacing from 150 mm to 75 mm also contributes notably to improved performance by increasing stiffness and further limiting displacement. These findings underscore the equal importance of optimizing both reinforcement spacing and configuration to achieve effective energy dissipation, greater stability, and resilience in RC columns exposed to extreme dynamic loads.

5. Conclusion

This research explores the effects of transverse reinforcement configurations, tie spacing, and axial load ratios on the blast performance of reinforced concrete (RC) columns. Through numerical simulations, the study highlights key design strategies for enhancing the resilience of RC columns under extreme dynamic conditions. The findings can be summarized as follows:

- **Impact of Transverse Reinforcement Configuration**: Advanced transverse reinforcement configurations, such as the double square (2S) arrangement, significantly improve structural performance by enhancing stress distribution, limiting lateral deformation, and increasing overall stability under blast loads.
- **Effect of Tie Spacing**: Reducing tie spacing from 150 mm to 75 mm provides measurable benefits by increasing stiffness and energy dissipation. These improvements are comparable to the effects of optimized reinforcement shapes, underscoring the importance of spacing as a design parameter.
- **Role of Axial Load Ratios (ALRs)**: Moderate ALRs improve column stability by pre-compressing the concrete core, reducing deformation and delaying failure. However, higher ALRs increase stress concentrations, leading to brittle, shear-dominated failure mechanisms.
- **Failure Mechanisms**: Columns with advanced transverse reinforcement exhibited localized and controlled damage, with the 2S configuration minimizing cracking and spalling.
- **Design Implications**: Combining optimized transverse reinforcement configurations, reduced tie spacing, and moderate axial load levels is essential for designing blast-resistant RC columns. These strategies enhance energy dissipation, ductility, and stability, contributing to safer and more resilient structural systems.

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