Semnan University

Journal of Modeling in Engineering

Journal homepage: https://modelling.semnan.ac.ir/

ISSN: 2783-2538



Comparison of the Behavior of Concrete and Composite Columns with the Same Mechanical Characteristics under Blast Load

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Received: 2024-03-18 Revised: 2025-09-18 Accepted: 2025-10-27

Abstract

This paper aims to investigate the behavior of concrete and composite columns subjected to blast loading through finite element analysis, validated against experiments adopted from the literature. To this end, after validating the finite element model, the behavior of two concrete columns with square and circular sections, and a composite column with a circular section with the same mechanical characteristics was investigated under the effect of blast loading. The results indicate that the greatest damage typically occurs near the columns' supports, with square sections showing higher vulnerability compared to circular sections. Introducing composite column can reduce this damage by approximately 59%, while also effectively decreasing maximum displacement and bending moment by up to 55%. Additionally, a parametric analysis was conducted to identify influential parameters on composite column behavior. The analysis suggests that selecting concrete with a compressive strength of 40 MPa represents an optimal choice for minimizing damage in the investigated columns, as further increases in concrete strength yield marginal benefits in terms of column damage and displacement.

Keywords

Blast load, Composite column, Reinforced concrete column, Finite element method, Damage.

1. Introduction

Blast loading represents a significant threat to structural safety due to its high intensity, short duration, and localized effects. Unlike conventional dynamic loads, such as earthquakes, blast-induced pressures may cause severe damage to individual structural members, potentially leading to progressive collapse [1]. Among structural components, columns play a critical role in maintaining the stability and load-carrying capacity of buildings. Therefore, understanding their behavior under blast loading is essential for developing more resilient structural systems.

Steel–concrete composite columns have attracted considerable attention due to their favorable mechanical properties and structural performance. The combination of steel and concrete allows these members to benefit from the tensile resistance and ductility of steel, together with the compressive strength of concrete. In particular, the confinement provided by steel tubes can improve the behavior of the concrete core and influence damage mechanisms under extreme loading conditions. Furthermore, the high strain rates associated with blast loading can significantly affect the mechanical response of structural materials [2].

Several experimental and numerical investigations have examined the behavior of concrete-filled steel tubular (CFST) and concrete-filled double-skin steel tubular (CFDST) columns subjected to blast loading [3–5]. These studies have highlighted the importance of steel confinement, concrete damage, energy absorption, and local deformation in determining structural response. Beyond these mechanisms, the overall response of blast-loaded columns is also influenced by cross-sectional properties, boundary conditions, and blast intensity. These aspects have been further explored through numerical and probabilistic approaches to evaluate structural damage, dynamic response, and the effects of blast stand-off distance [6–9].

Despite these developments, comparative investigations of reinforced concrete and steel–concrete composite columns with equivalent mechanical characteristics under identical blast conditions remain relatively limited. Such comparisons are important for distinguishing the effects of cross-sectional geometry and material configuration on structural

performance. Accordingly, the present study investigates the blast response of square and circular reinforced concrete columns and a circular composite column using an experimentally validated finite element model in LS-DYNA. Particular attention is given to deformation, damage distribution, bending response, and energy absorption, followed by a parametric investigation of the factors influencing composite-column performance.

2. Methodology

Three-dimensional nonlinear numerical simulations were performed using LS-PrePost for model preparation and LS-DYNA for transient dynamic analysis. Concrete was represented by the *MAT_CONCRETE_DAMAGE_REL3 formulation, intended to simulate nonlinear response and damage under high loading rates [10]. Steel reinforcement was modeled with *MAT_PLASTIC_KINEMATIC and was embedded in the concrete using *CONSTRAINED_LAGRANGE_IN_SOLID. The numerical formulation considered strain-rate effects in the materials. Eight-node solid elements were used for concrete and beam elements for reinforcing bars.

Validation was conducted using an experimental blast-loaded reinforced-concrete column documented in the literature [11,12]. The experimental configuration had a square section of approximately 89 mm side length, four 20 mm longitudinal reinforcing bars, and 10 mm stirrups at 50.8 mm spacing. The explosive charge was 7.087 kg of C4 (approximately 9.71 kg TNT equivalent), located about 1.067 m horizontally from the column and 0.305 m above the ground. The concrete compressive strength was approximately 42.23 MPa. The comparison focused on permanent column displacement, rather than exact reproduction of every transient displacement peak.

After validation, three columns with a height of approximately 2.121 m were analyzed: Type 1, square reinforced concrete; Type 2, circular concrete; and Type 3, circular concrete-filled steel tube. The configurations were proportioned to give the same mass and mass moments of inertia, allowing comparison of section form and constituent materials. Concrete compressive strength was 30 MPa in the baseline comparison. A 5 kg TNT charge was positioned approximately 1.067 m horizontally from the columns and 0.305 m above the ground; their bases were fixed. Subsequent parametric simulations varied the end restraints, blast stand-off distances (1, 2, and 3 m), TNT charge masses (1, 3, 5, and 7 kg), concrete compressive strengths (20, 30, 40, and 50 MPa), steel-tube thicknesses (1, 3, and 5 mm), and steel yield strengths (300, 500, and 700 MPa).

3. Results and Discussion

3.1. Model validation and comparative column response

The calculated permanent displacement in the validation model was 6.48 mm, compared with 6.30 mm measured experimentally, giving an error of approximately 2.86%. Although differences occurred in the initial peaks of the transient displacement records, the agreement in residual displacement supported the use of the numerical approach for the comparative analyses. Remaining discrepancies may reflect assumed material properties, incomplete structural details and simplified floor representation.

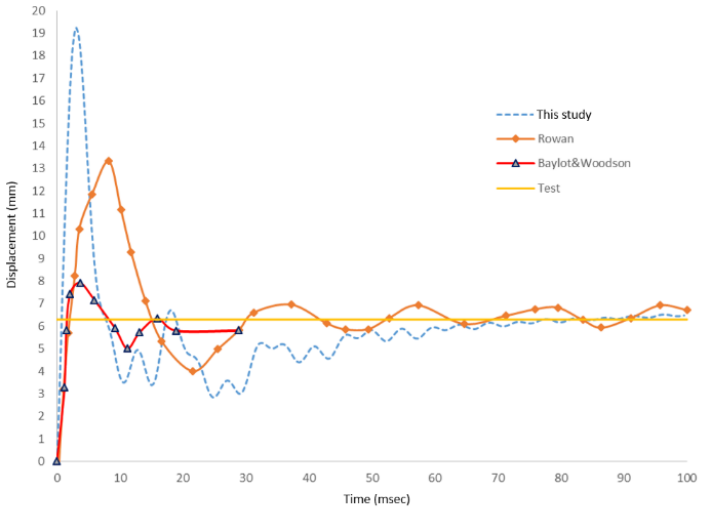


Figure 1. Comparison of the numerical and experimental validation responses.

The square concrete column had the least favorable response under the baseline blast, whereas the composite column showed the smallest free-end displacement and bending moment. The reported maximum displacements of Types 1, 2,

and 3 were 27.07, 19.91, and 12.14 mm, respectively. Their corresponding maximum bending moments were 349.1, 254.5, and 154.4 N·m. Thus, the composite configuration reduced peak displacement by approximately 55% and peak bending moment by approximately 56% relative to the square concrete column. Damage contours also indicated a reduction of approximately 59% for the composite design according to the source paper's damage comparison. The most pronounced damage generally developed close to the base restraint.

Table 1. Comparison of baseline responses of the three columns.

Response	Square RC (Type 1)	Circular concrete (Type 2)	Composite (Type 3)
Maximum displacement (mm)	27.07	19.91	12.14
Maximum bending moment (N·m)	349.1	254.5	154.4
Absorbed energy (J)	216	124	82

The absorbed energies of the three columns were 216, 124, and 82 J, respectively. Here, lower absorbed energy occurred alongside less displacement and damage in the composite model. Lower energy absorption alone does not imply better performance: stable plastic dissipation can be beneficial without severe damage. In the present comparison, the combined response measures establish the better performance of the composite column. The circular concrete section also outperformed the square section, consistent with the source study's interpretation that its lack of sharp corners reduces local stress concentration.

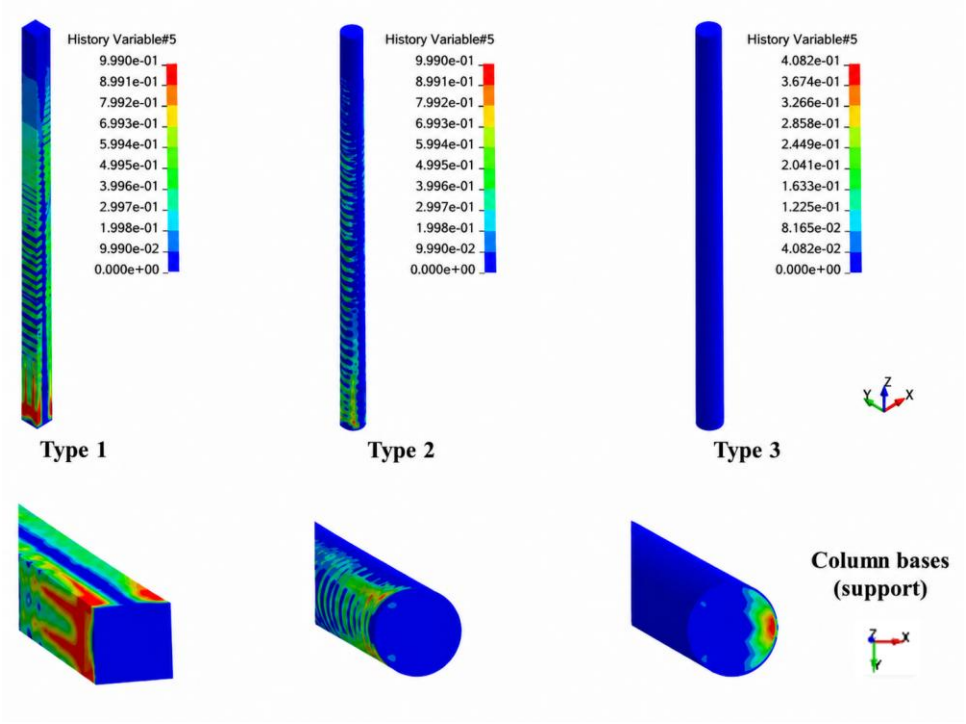


Figure 2. Damage contours of square concrete, circular concrete and composite columns.

3.2. Influence of blast intensity and structural restraints

The parametric simulations revealed a strong influence of boundary conditions on maximum lateral displacement. Restricting movement at the otherwise free end significantly decreased the response; therefore, idealizing a real connection as perfectly fixed or pinned may lead to misleading estimates. A realistic representation of partial rotational restraint deserves particular attention.

Increasing blast stand-off distance from 1 to 3 m reduced column displacement and the absorbed energy, with a nonlinear distance dependence. Conversely, increasing explosive mass from 1 to 7 kg at a fixed distance of 1 m increased lateral displacement. These trends highlight the roles of blast distance—also investigated in Momeni et al.'s reliability-based steel-column study [9]—and support restraints alongside charge mass.

3.3. Material-strength and steel-tube parameters

For the square concrete column, raising compressive strength from 20 to 50 MPa decreased maximum displacement from 50.24 to 38.33 mm. Results at 30 and 40 MPa were 45.01 and 41.25 mm, respectively. Damage contours for 40 and 50 MPa were broadly similar, suggesting that approximately 40 MPa was a reasonable strength selection for the specific

blast scenario examined; it is not a universally optimal value. Increasing strength beyond 40 MPa further reduced displacement, but with diminishing benefit.

In the composite column, increasing the steel-tube thickness from 1 to 3 and 5 mm decreased maximum displacement from 37.95 to 28.86 and 23.57 mm, respectively. By comparison, changing steel yield strength from 300 to 500 and 700 MPa had relatively little influence on the first displacement maximum, although changes became more apparent during later oscillations. For these models, the tube thickness was therefore a more effective parameter for controlling peak displacement than increasing nominal steel yield strength.

4. Conclusions

A validated LS-DYNA model was used to compare concrete and composite columns with equivalent mass and mass moments of inertia under localized blast loading. Within the investigated configurations, the circular concrete-filled steel tube displayed the smallest peak displacement, bending moment, and damage, while the square reinforced-concrete column was the most vulnerable. Approximately 55% reductions in peak displacement and bending moment and a reported 59% reduction in damage were associated with the composite alternative.

Parametric results established that stand-off distance, charge mass, support conditions, and tube thickness substantially affect response. Concrete compressive strength near 40 MPa provided a useful damage-control threshold for the tested conditions, whereas further strength increase offered diminishing benefit in damage reduction. Greater tube thickness was more effective than greater steel yield strength in reducing peak deformation. These findings provide comparative guidance for selecting blast-resistant column configurations, but should be applied with caution beyond the simulated geometries, loading scenarios, and assumed restraints. Future studies could examine alternative composite wrapping materials and more representative semi-rigid connections.

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