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Effect of Hollow Channel Cross-Section Shape on the Damage Mechanism of Reinforced Concrete Slabs Under Near-Field Blast Loading

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Abstract: Hollow-core reinforced concrete (RC) slabs are increasingly used for their reduced self-weight and integrated service voids, yet the influence of the internal channel cross-section shape on their behavior under near-field blast loading remains largely unexplored. Existing numerical studies on blast-loaded RC members focus almost exclusively on solid or circular-void cross-sections, leaving the systematic effect of void geometry unresolved. This study numerically investigates the contact detonation response of hollow-core RC slabs with three different channel cross-section shapes (square, circular, and hexagonal) using a coupled finite element method and smoothed particle hydrodynamics (FEM-SPH) approach in Abaqus/Explicit. The TNT charge is represented by the Jones-Wilkins-Lee (JWL) equation of state, concrete is modeled with the Concrete Damaged Plasticity (CDP) constitutive law, and an adaptive FEM-to-SPH conversion is employed in the contact region so that cratering and fragment ejection are captured without element-deletion artifacts. A parametric matrix of 48 models spanning three channel shapes, four lower-flange thicknesses (50-140 mm), and four charge masses (0.5-2.0 kg) was analyzed. The results show that the channel cross-section shape significantly governs blast resistance: the circular and hexagonal sections exhibit comparable performance and undergo approximately 20% lower mean bottom-flange displacement than the square section. The 90-degree corners of the square section promote premature crack initiation and concrete crushing through stress concentration. A critical lower-flange thickness is identified, beyond which the failure mode transitions from global flexural collapse to localized perforation. The predicted crater dimensions agree well with previously reported contact-explosion experiments.

Keywords: Hollow-core slab, Contact blast, FEM-SPH coupling, Channel geometry, Damage mechanism

Introduction

Protective reinforced concrete (RC) structures must resist blast loading, an extreme dynamic action characterized by a near-instantaneous rise of overpressure followed by rapid decay within a few milliseconds. Under such impulsive loading, concrete, being a brittle material, rapidly exceeds its elastic limit and may undergo severe local damage, spalling, and perforation. The conventional means of increasing blast resistance, namely adding mass and thickness, conflicts with the contemporary demand for lightweight and material-efficient construction. This tension has motivated the development of hollow-core RC slabs, in which periodic internal voids reduce self-weight while offering the potential to redistribute and attenuate blast-induced stresses (Savaş & Bakır, 2022; Bakır, 2026).

A substantial body of work has addressed the numerical simulation of blast-loaded RC members. Du et al. (2016) applied a coupled FEM-SPH method to model explosions inside pipes, capturing blast-wave propagation and dynamic fracture with a rate-dependent failure criterion. Karmakar and Shaw (2021) investigated the response of RC plates under blast loading using an FEM-SPH coupled framework, comparing several idealizations of the blast event and examining the effect of standoff distance and boundary conditions. Wang et al. (2023) employed an ALE-FEM-SPH coupling method to predict the spalling damage and fragment characteristics of RC slabs subjected to close-in detonation, validating fragment size and velocity distributions against experiments. Collectively, these studies established the FEM-SPH approach as an effective tool for blast problems that involve

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large deformation, discontinuity, and material fragmentation. However, they considered solid or single-void cross-sections; the systematic effect of the internal channel shape on the blast response of hollow-core slabs has not been addressed.

Although circular voids are the most common choice in hollow-core construction, the abrupt geometric transition at the tangent points of circular hollows can lead to irregular stress accumulation under highly dynamic loading, indicating that circular geometry is not necessarily optimal for blast resistance. Alternative void shapes such as square and hexagonal present different wall inclinations, corner angles, and load-transfer paths that may substantially alter the damage mechanism under contact blast. Square voids introduce sharp 90-degree corners at which stresses concentrate, whereas hexagonal voids form inclined web-walls that can redistribute load between adjacent cells through a Vierendeel-type framing action, in a manner analogous to the honeycomb cellular forms found in nature (Bakır, 2026). A direct, systematic comparison of these channel shapes under identical loading and boundary conditions is therefore required to guide the selection of void geometry for blast-resistant design.

The author's previous study (Bakır, 2026) focused on the parametric response and cross-validated surrogate modelling of hexagonal-hollow RC slabs subjected to standoff blast loading, using web thickness, charge mass, and hexagonal cell radius as the design variables. The present study addresses a distinct research question and uses a separate contact-detonation dataset: it systematically compares three channel cross-section shapes (square, circular, and hexagonal) while varying the lower-flange thickness and charge mass. Using a coupled FEM-SPH formulation in Abaqus/Explicit, a full-factorial parametric study of 48 models is carried out. The specific objectives are to quantify the influence of channel shape on peak deformation and energy dissipation, identify the failure-mode transition governed by lower-flange thickness, and characterize the crater morphology and damage mechanism associated with each void geometry. Thus, the present work extends the earlier geometry-specific standoff-blast study to a separate contact-blast regime and focuses on cross-sectional shape and local failure mechanisms rather than surrogate-model development.

Method

Coupled FEM-SPH Formulation

Contact and near-field detonation subject the concrete in the immediate vicinity of the charge to extreme distortion that a purely Lagrangian finite-element mesh cannot sustain without severe element tangling. To overcome this difficulty, an adaptive FEM-to-SPH conversion technique is employed. The slab is initially discretized entirely with Lagrangian finite elements. When a finite element in the contact region reaches a prescribed conversion criterion, here a maximum principal strain threshold, it is transformed into smoothed-particle-hydrodynamics (SPH) particles that inherit the mass, velocity, and momentum of the parent element. The deviatoric and volumetric stresses of the converted particles are reset, so that the particles carry only compressive pressure and thus represent the fragmented, cohesionless material realistically. The finite-element and particle domains are solved together, with forces transferred across the interface through hybrid elements, and because the kinetic energy of each converted element is preserved, the ejection velocity of the fragments is captured accurately. Cratering and material ejection are thereby reproduced without the mass and momentum inconsistency associated with pure element deletion.

In the present model the conversion is confined to the upper flange beneath the charge, the region that experiences direct contact loading and cratering, while the lower flange and the channel webs are retained as finite elements. This regional treatment reflects the physical observation that fragmentation is localized under the charge, keeps the particle count and computational cost manageable, and prevents spurious disintegration of the load-bearing lower flange, in agreement with the intact lower surfaces observed in contact-explosion experiments.

Explosive Model

The TNT charge is modeled with the Jones-Wilkins-Lee (JWL) equation of state, which describes the pressure p of the detonation products as a function of the relative volume V and the specific internal energy E , as given in Equation 1:

$$p = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where A , B , R_1 , R_2 , and ω are material constants determined from cylinder-expansion tests (Dobratz & Crawford, 1985). The JWL parameters adopted for TNT are listed in Table 1. The charge is placed in direct contact with the upper face of the slab above the central channel, and detonation is initiated at the charge center.

Table 1. JWL parameters for TNT

ρ (kg/m ³)	D (m/s)	A (GPa)	B (GPa)	R_1 / R_2	ω / E_0 (GPa)
1630	6930	371.2	3.231	4.15 / 0.95	0.30 / 7.0

Concrete and Reinforcement Models

The concrete is represented by the Concrete Damaged Plasticity (CDP) model (Lee & Fenves, 1998), which combines isotropic tensile-cracking and compressive-crushing damage with multi-hardening plasticity and captures the degradation of elastic stiffness under load reversal. The strain-rate sensitivity of concrete and steel under blast loading is commonly represented through dynamic increase factors (Malvar & Crawford, 1998). A compressive strength of 30 MPa (grade C30) is adopted, with the plasticity-surface parameters summarized in Table 2. The tensile and compressive hardening behavior and the associated damage-evolution data are prescribed in tabular form, defined such that the plastic strain increases monotonically to ensure numerical consistency. The steel reinforcement consists of two orthogonal mats modeled with two-node truss elements (T3D2) and coupled to concrete through an embedded-region constraint, representing a perfect-bond idealization appropriate for the global flexural response of interest.

Table 2. Concrete damaged plasticity parameters

f_c (MPa)	Dilation ψ	Eccentricity	f_{b0}/f_{c0}	K_c	Viscosity
30	36°	0.1	1.16	0.667	1×10^{-4}

Geometry, Boundary Conditions, and Mesh

The slab has overall plan dimensions of 1.0×2.0 m. A row of channels runs along the span, formed by a 50 mm upper flange, a channel of 150 mm height, and a lower flange whose thickness is varied parametrically. Three channel cross-section shapes (square, circular, and hexagonal) are considered (Figure 1), each generating a distinct wall geometry between adjacent voids while maintaining a comparable void size. The slab rests on a soil-type support, idealized by restraining the vertical displacement of the bottom surface while leaving the in-plane directions free, reproducing the support condition of the reference experimental configuration (Savaş & Bakır, 2022). The concrete domain is discretized with eight-node reduced-integration hexahedral elements (C3D8R) with enhanced hourglass and distortion control. The contact region beneath the charge uses a finer mesh (10 mm) to resolve the FEM-to-SPH conversion, whereas the remainder of the slab uses a coarser mesh (20 mm) and remains purely Lagrangian; the reinforcement is discretized with T3D2 truss elements embedded in the concrete host.

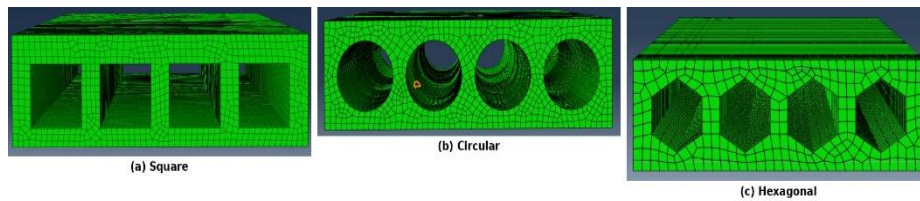


Figure 1. Finite-element models of the three channel shapes

Parametric Study

A full-factorial parametric matrix of 48 models was generated by combining three channel shapes, four lower-flange thicknesses, and four TNT charge masses, as summarized in Table 3. All other modeling choices (reinforcement layout, constitutive parameters, boundary conditions, and integration settings) were held constant,

so that the influence of the three design variables could be isolated. From each simulation the peak bottom-flange displacement, the crater depth, and the components of the energy balance were extracted

Table 3. Parametric design matrix

Variable	Levels	Count
Channel shape	Square, Circular, Hexagonal	3
Lower-flange thickness	50, 80, 110, 140 mm	4
TNT charge mass	0.5, 1.0, 1.5, 2.0 kg	4

Results and Discussion

Effect of Channel Cross-Section Shape

The channel cross-section shape has a pronounced effect on the blast resistance of the slab. Table 4 reports the mean peak bottom-flange displacement for each shape, averaged over all thickness and charge levels. The circular (84.2 mm) and hexagonal (87.0 mm) sections perform comparably and exhibit the smallest mean displacement, while the square channel undergoes the largest displacement (106.7 mm). The circular and hexagonal sections are therefore approximately 20% more effective than the square section in limiting the bottom-flange deflection.

This ranking is explained by the load-transfer geometry of each void. In the square channel, the flat soffit of the upper flange spans the full void width without inclined support, and the sharp 90-degree corners act as stress raisers that promote premature crack initiation and concrete crushing; the loaded flange therefore deflects most. By contrast, the circular section provides a smooth load-transfer path without sharp corners, while the inclined walls of the hexagonal section redistribute the load between adjacent cells. These geometric characteristics explain why the circular and hexagonal channels exhibit comparable responses and lower mean bottom-flange displacement than the square channel. The finite-element models of the three channel cross-section shapes are shown in Figure 1.

Table 4. Mean bottom displacement by shape

Channel shape	Mean displacement (mm)	Rel. to square
Circular	84.2	-21.1%
Hexagonal	87.0	-18.5%
Square	106.7	reference

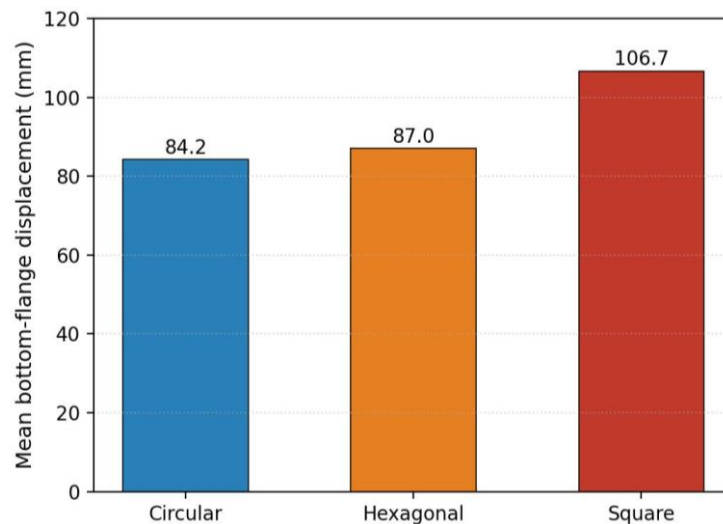


Figure 2. Mean bottom displacement by shape

Effect of Lower-Flange Thickness

The lower-flange thickness strongly governs deformation and the failure mode. Table 5 lists the peak bottom-flange displacement as a function of thickness for the three shapes at a fixed charge mass of 1.0 kg. For every shape, increasing the thickness from 50 to 140 mm reduces the displacement by a factor of four to five (for

example, from 136.4 to 28.1 mm in the square section). The reduction is steepest between 50 and 110 mm and diminishes beyond approximately 110 mm, indicating a region of diminishing returns and the existence of a critical lower-flange thickness above which further thickening yields little additional benefit. This trend is illustrated in Figure 3.

Two distinct failure regimes are observed. For thin lower flanges combined with large charges, the entire cross-section is driven downward and the slab fails by global flexural collapse, with the bottom flange displacing more than the crater depth on the loaded face. For thick lower flanges, the damage remains localized: the upper flange is perforated and a crater forms, but the lower flange and the reinforcement retain their integrity, corresponding to localized perforation. The transition between these regimes is controlled by the lower-flange thickness in combination with the charge mass.

Table 5. Bottom displacement (mm) vs thickness (M = 1.0 kg)

Shape	50 mm	80 mm	110 mm	140 mm
Square	136.4	93.0	54.6	28.1
Circular	109.5	49.1	30.6	20.6
Hexagonal	100.1	47.0	31.1	—

Dashes denote a small number of configurations that did not reach numerical completion under the initial-shock convergence limit.

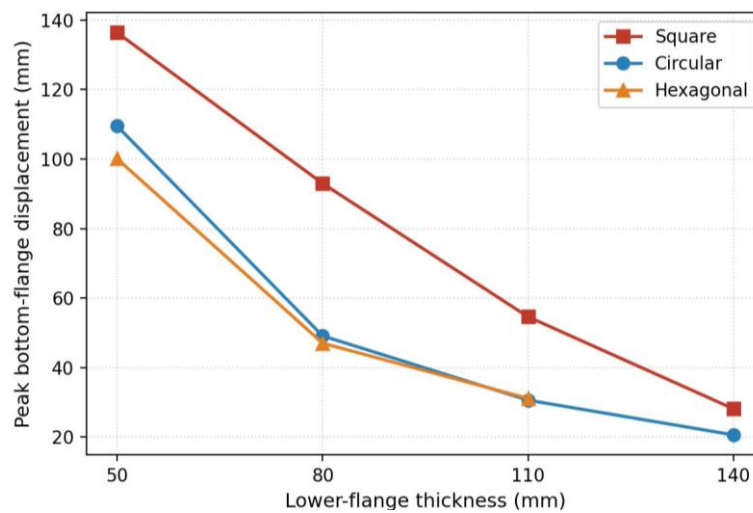


Figure 3. Displacement versus lower-flange thickness

Effect of Charge Mass and Energy Dissipation

Increasing the charge mass raises the deformation in a strongly nonlinear manner. For the square section with an 80 mm lower flange, the peak bottom-flange displacement increases from a negligible value at 0.5 kg to 93.0 mm at 1.0 kg, 165.6 mm at 1.5 kg, and 204.4 mm at 2.0 kg. At the lightest charge the upper flange is only locally damaged and the bottom flange is essentially undisturbed, whereas at the heaviest charge the section approaches global collapse. This confirms that, for a given geometry, the charge mass is the dominant driver of the overall response, and that the beneficial effect of the channel shape is most valuable in the intermediate range, where the response is sensitive to the load-transfer geometry.

The energy balance provides further insight. For the square section with an 80 mm lower flange under a 1.0 kg charge, the kinetic energy of the ejected material and detonation products dominates the balance (of the order of 3.6 MJ), while the energy dissipated by concrete damage and plasticity is much smaller (of the order of 0.18 MJ). The proportion of energy absorbed by the slab, rather than transmitted to the ejected fragments, is greatest for the geometries that distribute the load most effectively, consistent with the displacement ranking above.

Crater Morphology and Damage Mechanism

The adaptive FEM-to-SPH conversion reproduces the crater and fragment ejection on the loaded face while preserving the integrity of the lower flange. In all configurations the crater develops on the upper flange directly

beneath the charge, with the converted particles ejected away from the slab, while the lower flange and channel webs remain as finite elements and do not perforate, consistent with the intact lower surfaces reported in contact-explosion experiments. The square section shows the most extensive tensile-damage field around the crater, with damage bands emanating from the sharp corners, whereas the circular and hexagonal sections confine the damage to a smaller region, as compared in Figure 4. A cross-sectional view confirming the intact lower flange is shown in Figure 5. The predicted crater dimensions are in good agreement with the experimental crater measurements reported by Savaş and Bakır (2022) on hollow-core RC slabs subjected to contact charges, supporting the validity of the modeling approach.

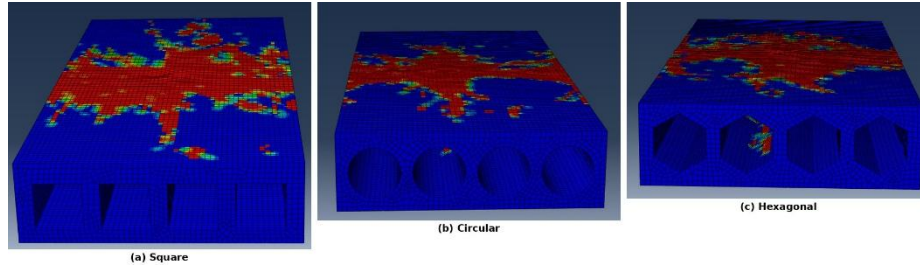


Figure 4. Tensile-damage distribution for the three shapes

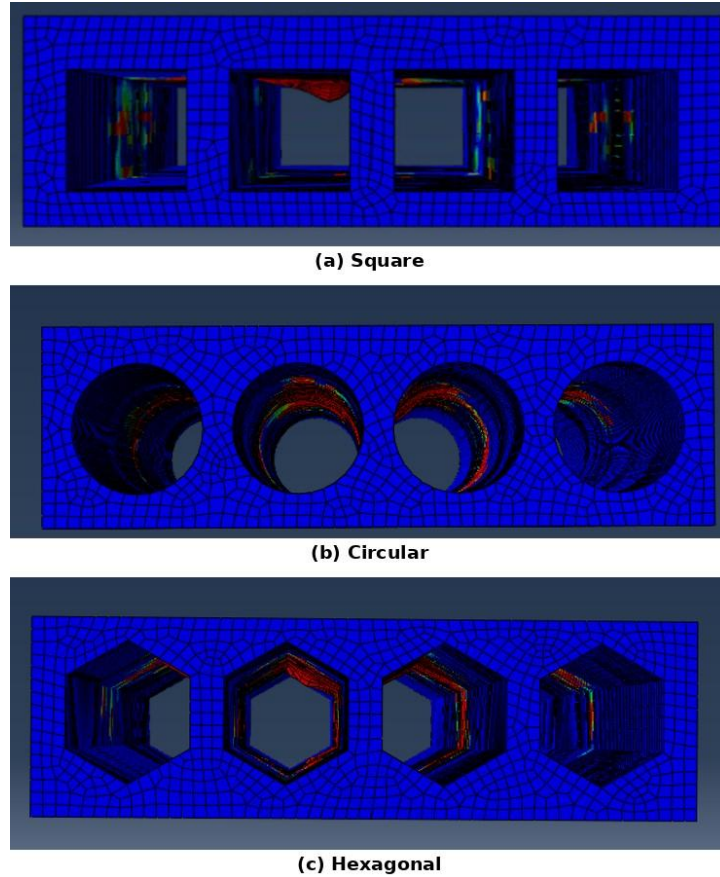


Figure 5. Cross-sections showing intact lower flange

Conclusion

This study numerically investigated the effect of the internal channel cross-section shape on the damage mechanism of hollow-core reinforced concrete slabs under near-field blast loading, using a coupled FEM-SPH approach in Abaqus/Explicit with a full-factorial parametric study of 48 models. Within the investigated contact-detonation dataset, the channel cross-section shape significantly influenced the blast response of the slab: the circular and hexagonal channels perform comparably and are the most effective in limiting the bottom-flange deflection, giving a mean displacement approximately 20% lower than the square channel. The comparable response of the circular and hexagonal sections independently corroborates the trend reported in the author's

earlier standoff-blast study (Bakır, 2026), although the present result is obtained from a separate loading regime and parametric matrix. Their favorable behavior relative to the square section is attributed to their curved and inclined walls, which distribute the applied load more uniformly, whereas the sharp 90-degree corners of the square section act as stress raisers that promote premature cracking and crushing.

The lower-flange thickness was found to strongly control both the magnitude of deformation and the failure mode. A critical thickness, of the order of 110 mm for the configurations studied, separates a global flexural-collapse regime from a localized-perforation regime, and thickening beyond this value yields diminishing returns. The adaptive FEM-to-SPH conversion reproduced the crater and fragment ejection on the loaded face without element-deletion artifacts and preserved the integrity of the lower flange, in agreement with experimental observations, and the predicted crater dimensions matched previously reported contact-explosion measurements. Overall, the results indicate that the internal void geometry is an effective design parameter for blast-resistant hollow-core slabs, and that the hexagonal geometry offers performance comparable to the conventional circular void while avoiding the stress concentrations of the square section.

Recommendations

Future work should extend the present study to additional charge standoffs to cover the full near-field to far-field range, incorporate bond-slip and strain-rate (dynamic increase factor) effects in the constitutive models for improved local accuracy, and examine the fragment size and velocity distributions in greater detail. A mesh-convergence study across the loading regimes and an experimental validation campaign specific to the non-circular channel shapes are also recommended to further establish the reliability of numerical predictions.

Scientific Ethics Declaration

* The author declares that the scientific, ethical, and legal responsibility for this article published in EPSTEM belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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