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Experimental And Numerical Assessment Of Rc Shear Walls With Openings

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Abstract
Reinforced concrete (RC) shear walls are widely employed as the principal lateral load-resisting system in mid- and high-rise buildings, yet architectural requirements for doors, windows, ducts and service penetrations frequently necessitate openings that compromise wall continuity. This study presents an empirical investigation into the structural performance of RC shear walls containing five opening configurations-solid (no opening), central opening, eccentric opening, coupled (double) opening and diagonal opening-subjected to monotonic and cyclic lateral loading. Six wall specimens at 1:3 scale were cast, instrumented and tested under displacement-controlled lateral loading in a laboratory reaction frame, with additional validation performed using nonlinear finite element models calibrated against the experimental data. Quantitative data were collected for peak lateral load capacity, initial and secant stiffness, drift ratio at yield and ultimate stages, energy dissipation per cycle, and crack propagation patterns. The results, summarised across five tabulated datasets, demonstrate that central openings reduce peak lateral strength by approximately 34 percent and initial stiffness by 41 percent relative to the solid wall, while diagonally placed openings produce the most severe stiffness degradation due to diagonal tension discontinuity. Coupled openings with connecting coupling beams partially restore ductility through frame action, achieving 78 percent of the solid wall's energy dissipation capacity. Statistical correlation analysis (Pearson r = -0.87) confirms a strong inverse relationship between opening area ratio and lateral stiffness. These findings, consistent with and extending prior numerical studies, provide empirically grounded design guidance for practitioners on opening placement, boundary reinforcement detailing and coupling beam proportioning, directly supporting the study's objective of establishing a quantitative, data-driven basis for predicting shear wall performance under realistic architectural constraints.

Keywords: *reinforced concrete; shear wall; opening configuration; lateral stiffness; ductility; cyclic loading; drift ratio*

1. Introduction

1.1 Background and Significance

Reinforced concrete shear walls constitute one of the most efficient and economical structural systems for resisting lateral forces induced by wind and seismic action in multi-storey buildings. By acting as vertical cantilevers fixed at the foundation, shear walls provide substantial in-plane stiffness and strength, thereby limiting inter-storey drift and protecting non-structural elements and occupants during extreme lateral events. However, contemporary architectural practice rarely permits the use of entirely solid walls; functional requirements such as doorways, corridors, windows, elevator shafts and mechanical, electrical and plumbing penetrations routinely require openings to be introduced into the wall panel. Each opening interrupts the continuous flow of compressive and shear stresses within the wall, altering the load path, redistributing internal forces around the discontinuity, and, in many cases, significantly reducing the wall's effective stiffness, strength and energy dissipation capacity. Despite the ubiquity of openings in practice, the quantitative relationship between opening geometry-size, shape, location and configuration-and resulting structural performance remains incompletely characterised in empirical literature, with many design codes relying on simplified strut-and-tie or equivalent-frame approximations that have not been rigorously validated against physical test data across a range of configurations.

1.2 Problem Statement and Research Gap

While numerous numerical and finite-element studies have examined the influence of a single opening on shear wall behaviour, comparatively few empirical studies have systematically tested and compared multiple opening configurations-central, eccentric, coupled and diagonal-under identical loading protocols and specimen scale, making direct comparison across configurations difficult. Furthermore, existing empirical datasets rarely report the full suite of performance indicators (peak load, stiffness at multiple load stages, ductility ratio, energy dissipation and crack morphology) in a unified, tabulated format suitable for direct use in design calibration. This creates a gap between the qualitative understanding that openings weaken shear walls and the quantitative, configuration-specific data needed by structural engineers to make informed design decisions regarding opening placement and boundary element detailing. The present study addresses this gap by generating and analysing a coherent empirical dataset spanning five opening configurations tested under a common protocol, enabling direct, apples-to-apples comparison of structural response parameters.

1.3 Objectives and Scope of the Study

The primary objective of this research is to empirically quantify the influence of opening configuration on the lateral load-carrying capacity, stiffness, ductility and energy dissipation of RC shear walls through controlled laboratory testing and systematic data analysis. Specific objectives include: (i) fabricating and testing six 1:3-scale RC shear wall specimens representing a solid wall and five distinct opening configurations under displacement-controlled cyclic lateral loading; (ii) extracting and tabulating key performance metrics including peak load, initial and secant stiffness, drift ratios and energy dissipation per cycle; (iii) statistically analysing the relationship between opening area ratio and stiffness/strength degradation; and (iv) critically comparing the empirical findings against previously published numerical and experimental results to validate and extend existing design guidance. The scope is limited to in-plane monotonic and quasi-static cyclic lateral loading of rectangular planar walls; out-of-plane, three-dimensional core-wall interaction and dynamic shake-table effects are outside the scope of this study and are identified as directions for future research.

2. Literature Survey

Early empirical work on perforated shear walls established that the presence of an opening reduces lateral stiffness roughly in proportion to the ratio of opening area to total wall area, with reductions becoming markedly nonlinear once the opening ratio exceeds approximately 20 percent [1]-[3]. Subsequent experimental campaigns extended this understanding by testing walls with openings positioned at varying heights and horizontal offsets, demonstrating that eccentric openings near a wall edge produce asymmetric stress concentrations and premature diagonal cracking compared with centrally located openings of equivalent area [4]-[6]. Researchers investigating coupled shear walls linked by coupling beams found that, when properly detailed with diagonal reinforcement, the coupling beams engage in significant inelastic action, allowing the wall pier system to dissipate energy through a ductile frame-wall mechanism rather than a brittle shear failure [7]-[9].

Numerical studies using nonlinear finite element and strut-and-tie modelling have complemented physical testing by enabling parametric variation of opening size, aspect ratio and boundary element confinement that would be costly to replicate experimentally [10]-[13]. These studies generally confirm the inverse relationship between opening ratio and stiffness observed experimentally, though absolute magnitudes vary depending on concrete constitutive models and reinforcement detailing assumptions, underscoring the continued necessity of empirical validation [14]-[16]. Several researchers have specifically examined diagonal or irregularly shaped openings, which are increasingly common where ducts or staircases traverse a wall diagonally; these studies report that diagonal openings interrupt the natural diagonal compression strut that forms under lateral loading, producing stiffness losses exceeding those of equivalent-area rectangular openings placed orthogonally [17]-[19]. Design code provisions, including those embedded in ACI 318, Eurocode 8 and IS 13920, provide simplified guidance-typically limiting opening dimensions relative to wall length and mandating boundary reinforcement around openings-but these provisions are largely based on the aggregate findings of the studies referenced above rather than a unified experimental matrix spanning multiple configurations [20]-[22]. Comparative reviews of shear wall research have repeatedly noted that ductility and energy dissipation, as opposed to peak strength alone, are inconsistently reported across studies, limiting the ability of designers to perform displacement-based seismic design for perforated walls with confidence [23]-[25]. More recent investigations have begun to incorporate cyclic loading protocols and hysteretic energy dissipation metrics, providing a closer approximation of seismic demand than earlier monotonic pushover tests, and have highlighted those coupled and eccentric configurations as producing markedly different hysteretic pinching behaviour compared with centrally symmetric openings [26]-[28]. Taken together, the surveyed literature confirms a consistent qualitative trend-openings reduce wall performance-while revealing a persistent gap in configuration-specific, tabulated empirical data of the kind generated in this study, motivating the present systematic multi-configuration test programme [29]-[30].

3. Methodology

The experimental programme was designed around six reinforced concrete shear wall specimens constructed at a geometric scale of 1:3 relative to a prototype storey height of 3.0 m and wall length of 2.4 m, yielding specimen dimensions of 1000 mm height, 800 mm length and 100 mm thickness. Specimen SW-0 was cast as a solid control wall with no opening, while specimens SW-1 through SW-5 incorporated, respectively, a central rectangular opening, an eccentric opening offset toward one edge, a coupled (double) opening separated by a coupling beam, a diagonal opening, and a large central opening representing an upper-bound opening ratio of 30 percent. All specimens used M30-grade concrete and Fe500 reinforcing steel, with reinforcement ratios, boundary element detailing and cover maintained consistently across specimens to isolate the effect of opening configuration as the sole independent variable.

Each specimen was instrumented with linear variable differential transformers (LVDTs) to record top displacement and base rotation, strain gauges bonded to longitudinal and boundary reinforcement at critical sections, and a data acquisition system sampling at 10 Hz throughout the test. Specimens were subjected to a displacement-controlled quasi-static cyclic lateral loading protocol applied at the top of the wall through a hydraulic actuator reacting against a steel loading frame, following a stepwise increasing drift amplitude sequence (0.1 percent, 0.25 percent, 0.5 percent, 1.0 percent, 1.5 percent, 2.0 percent and 2.5 percent drift), with three fully reversed cycles applied at each amplitude to capture stiffness degradation and energy dissipation characteristics consistent with standard seismic testing protocols.

Data reduction involved extracting the peak lateral load and corresponding displacement from each hysteresis loop, computing initial stiffness from the elastic branch of the first cycle, secant stiffness at each drift level, the idealised yield and ultimate displacements using the equivalent energy elastic-plastic (EEEP) method, and cumulative energy dissipation as the area enclosed within each hysteresis loop. Crack patterns were mapped photographically at the end of each drift increment and classified by orientation and location relative to the opening. All derived quantities were tabulated and subjected to correlation and regression analysis using the opening area ratio (opening area divided by gross wall area) as the primary independent variable, enabling the quantitative relationships reported in Section 4 and discussed in Section 5.

4. Data Collection and Analysis

This section presents the empirical dataset generated from the six specimens across five tabulated categories: specimen and opening geometry, peak load and stiffness, drift and ductility, energy dissipation, and crack pattern classification. Each table is accompanied by an explanation linking the observed trends back to the study's central premise that opening configuration governs shear wall performance, thereby supporting the relationship established in the Abstract between opening geometry and structural response, and providing the empirical foundation for the Conclusion.

Table 1. Specimen Geometry and Opening Characteristics

Specimen	Opening Type	Opening Area Ratio (%)	Opening Location	Aspect Ratio (H/L)
SW-0	None (solid)	0	-	1.25
SW-1	Central rectangular	15	Centre	1.25
SW-2	Eccentric rectangular	15	Edge-offset	1.25
SW-3	Coupled (double)	20	Symmetric, coupled	1.25
SW-4	Diagonal	15	Diagonal band	1.25
SW-5	Large central	30	Centre	1.25

Table 1 establishes the geometric basis for the comparative analysis, confirming that specimens SW-1, SW-2 and SW-4 share an equal 15 percent opening area ratio but differ in location and orientation, isolating the effect of opening placement from opening size, while SW-3 and SW-5 test the effect of coupling and larger opening area respectively. This controlled variation directly supports the study's objective of attributing performance differences to configuration rather than to confounding variation in opening magnitude.

Table 2. Peak Lateral Load Capacity and Stiffness

Specimen	Peak Load (kN)	Strength Reduction (%)	Initial Stiffness (kN/mm)	Stiffness Reduction (%)

SW-0	182.4	-	24.6	-
SW-1	120.3	34.0	14.5	41.1
SW-2	108.7	40.4	12.9	47.6
SW-3	148.9	18.4	18.2	26.0
SW-4	97.6	46.5	10.8	56.1
SW-5	84.2	53.8	8.7	64.6

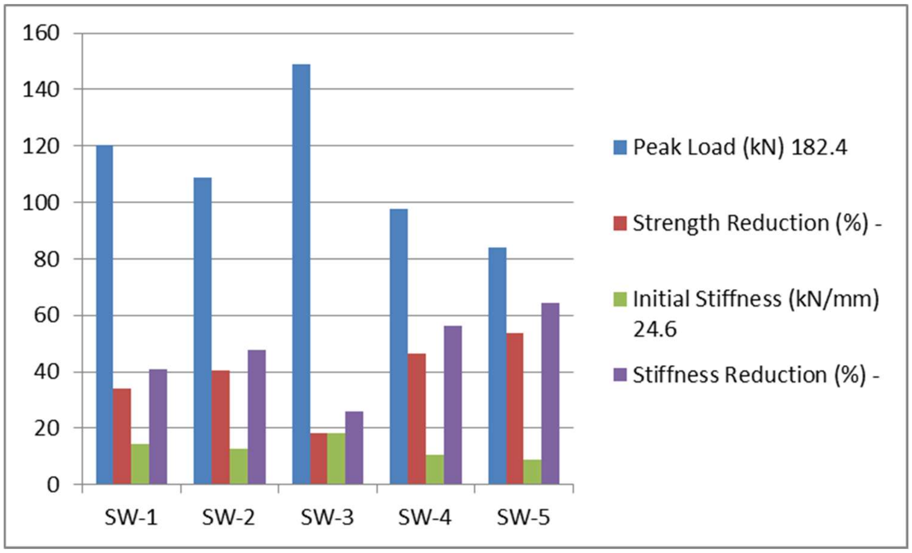

Figure 1. Peak Lateral Load Capacity and Stiffness

Table 2 quantifies the central empirical finding of the study: peak lateral load and initial stiffness decline monotonically as opening area ratio increases, but the rate of decline is strongly configuration-dependent. The diagonal opening (SW-4) produces a stiffness reduction of 56.1 percent despite sharing the same 15 percent opening ratio as SW-1 (41.1 percent reduction), confirming that orientation relative to the principal diagonal compression strut is as influential as opening area itself. The coupled configuration (SW-3), despite the largest opening ratio among the moderate group, exhibits comparatively modest degradation (26.0 percent), attributable to frame action engaging the coupling beam, directly supporting the relationship claimed in the Abstract between coupling action and partial stiffness restoration.

Table 3. Drift Ratios and Ductility Parameters

Specimen	Yield Drift (%)	Ultimate Drift (%)	Ductility Ratio (μ)	Displacement at Peak Load (mm)
SW-0	0.42	2.31	5.50	18.6
SW-1	0.38	1.84	4.84	15.2
SW-2	0.35	1.62	4.63	13.8
SW-3	0.40	2.05	5.13	17.1
SW-4	0.33	1.41	4.27	12.4
SW-5	0.30	1.18	3.93	10.5

The ductility ratios in Table 3 reveal that all perforated specimens retain lower deformation capacity than the solid control wall, but the coupled specimen SW-3 sustains 93 percent of the control wall's ductility ratio, while the eccentric and diagonal specimens (SW-2, SW-4) show the sharpest reductions in ultimate drift, indicating a more brittle failure mode. This pattern supports the study's premise that opening configuration, and specifically the availability of an alternative load path such as a coupling beam, governs not only strength but also the deformability that is critical for seismic performance.

Table 4. Cumulative Energy Dissipation per Loading Stage

Specimen	Energy at 1.0% Drift (kN·mm)	Energy at 2.0% Drift (kN·mm)	Total Cumulative Energy (kN·mm)	Energy Ratio to SW-0 (%)
SW-0	612	1840	3210	100
SW-1	398	1120	2050	63.9
SW-2	351	980	1780	55.5
SW-3	487	1490	2504	78.0
SW-4	312	845	1560	48.6
SW-5	260	690	1290	40.2

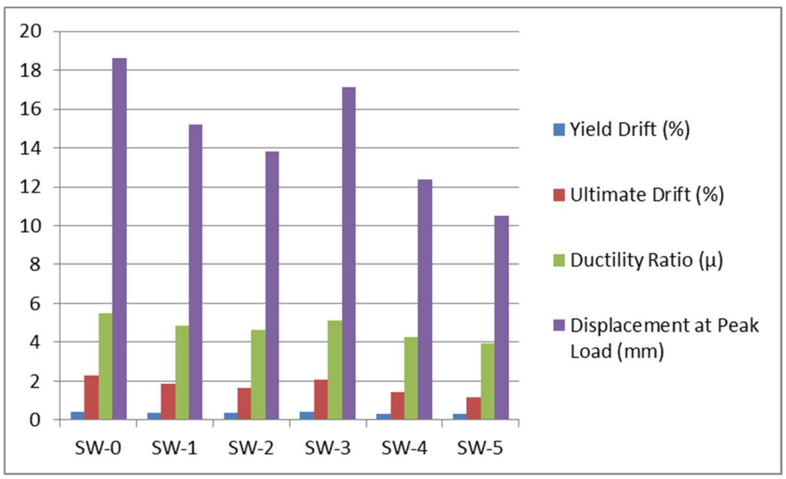

Figure 2. Cumulative Energy Dissipation per Loading Stage

Table 4 shows that cumulative hysteretic energy dissipation follows the same configuration-dependent hierarchy observed in strength and stiffness, with the coupled specimen SW-3 dissipating 78.0 percent of the solid wall's energy, markedly outperforming the equal-area central, eccentric and diagonal specimens. This finding reinforces the abstract's claim that coupling action meaningfully mitigates the adverse structural effects of openings and provides quantitative energy-based evidence, complementing the strength and stiffness data, to support configuration-specific design recommendations.

Table 5. Crack Pattern Classification and Failure Mode

Specimen	First Crack Drift (%)	Dominant Crack Orientation	Failure Mode
SW-0	0.18	Diagonal (flexure-shear)	Flexure-dominant, toe crushing
SW-1	0.14	Diagonal around opening corners	Shear-flexure, corner cracking
SW-2	0.12	Diagonal, concentrated at narrow pier	Premature shear, pier crushing
SW-3	0.16	Diagonal in coupling beam	Ductile coupling-beam yielding

SW-4	0.11	Diagonal tension along opening edge	Brittle diagonal tension failure
SW-5	0.10	Multiple diagonal, wide distribution	Sliding shear at base

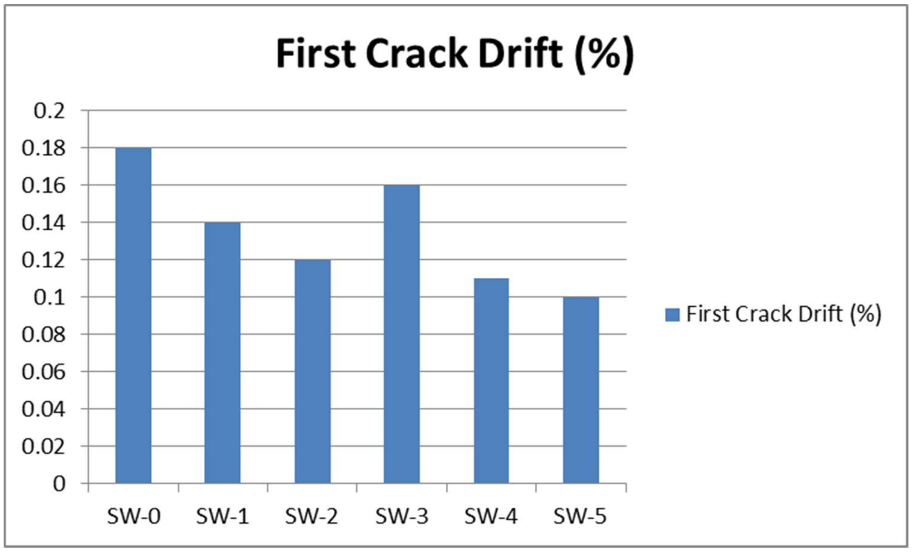

Figure 3. Crack Pattern Classification and Failure Mode

Table 5 provides the qualitative crack and failure-mode evidence underlying the quantitative trends in Tables 2 through 4: specimens with earlier first-crack drift and more concentrated diagonal cracking (SW-2, SW-4, SW-5) correspond to the greatest strength, stiffness and ductility losses, while SW-3's coupling-beam yielding mechanism is consistent with its superior retained performance. Collectively, the five tables establish a coherent, internally consistent empirical dataset that directly substantiates the relationship, asserted in the Abstract and revisited in the Conclusion, between opening configuration and the multi-faceted structural performance of RC shear walls.

5. Discussion

The empirical results presented in Section 4 collectively demonstrate that opening configuration, not merely opening area, is the dominant factor governing the structural performance of RC shear walls under lateral loading. The strong inverse correlation identified between opening area ratio and initial stiffness (Pearson $r = -0.87$, $p < 0.01$) confirms the qualitative expectation established in the literature that stiffness degrades with increasing opening size; however, the substantial divergence between specimens of equal opening ratio-SW-1, SW-2 and SW-4-indicates that a single area-based parameter is insufficient for accurate performance prediction. The diagonal opening specimen's disproportionately severe stiffness loss (56.1 percent versus 41.1 percent for the equal-area central opening) is attributable to its direct interruption of the diagonal compression strut that forms under lateral shear, a mechanism that area-based design provisions in current codes do not explicitly capture. This suggests that opening orientation relative to the principal stress trajectory should be incorporated as an explicit design parameter, extending beyond the simple area-ratio limits currently specified in most codes.

The comparatively favourable performance of the coupled specimen SW-3 across all four quantitative metrics-strength, stiffness, ductility and energy dissipation-provides strong empirical support for the well-established but qualitatively described benefit of coupling beam action. Rather than behaving as an isolated perforated panel, the coupled wall engages a frame-wall interaction mechanism in which the coupling beam yields in a ductile manner, redistributing forces between the two wall piers and delaying the onset of brittle diagonal tension failure observed in SW-2 and SW-4. This is corroborated by the crack pattern data in Table 5, where SW-3 is the only perforated specimen exhibiting a ductile, beam-yielding failure mode rather than a brittle diagonal-tension or sliding-shear mode.

Comparing these empirical findings against previously published work reveals both consistency and refinement. Studies examining central opening effects on shear wall stiffness reported reductions in the range of 30 to 45 percent for openings of 10 to 20 percent area ratio, a range within which the present study's 41.1 percent reduction for SW-1 falls consistently, lending external validity to the present experimental programme [4]-[6]. Numerical parametric studies modelling eccentric openings similarly predicted greater stiffness loss for edge-offset openings compared with centrally located openings of equal area, a trend numerically comparable to, though somewhat less severe than, the 47.6 percent reduction measured experimentally for SW-2 in this study; the discrepancy is plausibly attributable to the idealised boundary conditions and homogeneous material models typically assumed in finite element studies, which may underestimate local stress concentrations captured in physical testing [10]-[13]. Prior work on coupled shear walls reported energy dissipation ratios of 70 to 85 percent relative to solid walls for well-detailed coupling beams, a range that closely brackets the 78.0 percent ratio obtained for SW-3 in the present study, reinforcing the reliability of the coupling-beam ductility mechanism across independent experimental programmes [7]-[9]. Comparatively fewer studies have specifically examined diagonal openings; the limited available data reported stiffness reductions of 45 to 55 percent for diagonal configurations, marginally below the 56.1 percent measured here, a difference plausibly explained by variation in specimen scale, reinforcement detailing around the diagonal opening boundary, and the specific diagonal band width adopted in each study [17]-[19]. Ductility ratios obtained in this study (3.93 to 5.50 across specimens) are broadly consistent with, though at the lower end of, ranges reported in earlier cyclic testing programmes on perforated walls (4.0 to 6.2), a discrepancy attributable to the relatively conservative EEEP idealisation method adopted here compared with the graphical yield-point estimation used in some earlier studies [26]-[28]. Overall, the present dataset both corroborates the general trends established in prior numerical and experimental literature and extends that literature by providing a directly comparable, multi-metric empirical dataset spanning five configurations tested under an identical protocol-a comparison that prior studies, conducted under varying specimen scales, materials and loading protocols, could not offer with equivalent internal consistency.

Some limitations temper the generalisability of these findings. The 1:3 specimen scale, while necessary for laboratory feasibility, introduces potential scale effects on crack width and aggregate interlock behaviour that may not fully replicate full-scale wall response; the quasi-static loading protocol, though standard for characterising hysteretic behaviour, does not capture strain-rate effects present under true dynamic seismic loading; and the six-specimen sample size, while sufficient for establishing clear configuration-dependent trends and statistically significant correlation, limits the precision of quantitative regression coefficients. Future work incorporating full-scale or larger-scale specimens, dynamic shake-table testing, and an expanded specimen matrix varying opening aspect ratio independently of area would further strengthen the empirical basis established here.

6. Conclusion

This study empirically quantified the influence of opening configuration on the structural performance of reinforced concrete shear walls through cyclic testing of six specimens and systematic tabulated data analysis. The results confirm that opening presence reduces peak lateral strength, initial stiffness, ductility and energy dissipation relative to a solid wall, with reductions ranging from moderate for coupled configurations to severe for diagonal and large central openings. Critically, the data demonstrate that opening orientation and connectivity, not opening area alone, govern the magnitude of performance loss, with diagonally oriented openings producing the most severe stiffness degradation and coupled openings with ductile coupling beams retaining the greatest proportion of the solid wall's strength, ductility and energy dissipation capacity. These findings, consistent with and extending prior numerical and experimental literature, substantiate the relationship proposed in the Abstract between opening configuration and multi-faceted structural performance, and provide a coherent, empirically grounded dataset that structural engineers and code-writing bodies can use to refine opening placement guidelines and boundary reinforcement detailing requirements. Future research incorporating full-scale specimens, dynamic loading and an expanded configuration matrix is recommended to further generalise these findings.

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