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Full Length Article

Structural Behavior Of Reinforced Concrete Shear Walls With Openings: A Review

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Abstract
Reinforced concrete (RC) shear walls are primary lateral-load resisting elements in medium- and high-rise buildings, yet their performance is frequently interrupted by architectural and service openings required for doors, windows, ducts and corridors. This review research paper synthesizes past experimental, analytical and numerical work on RC shear walls with different opening configurations, with emphasis on how opening size, shape, position, number and reinforcement detailing influence strength, stiffness, ductility, energy dissipation and failure mode. The reviewed literature indicates that openings reduce the effective wall web area and disturb diagonal compression fields, causing stress concentration at corners and premature cracking when boundary elements, coupling beams and diagonal reinforcement are insufficient [1]. Centrally placed small openings can often be accommodated with moderate reductions in capacity, whereas large, eccentric, staggered or multiple openings may transform a solid wall into a coupled wall system governed by pier flexure, spandrel shear and localized crushing. Meta-analysis of reported trends shows that opening area ratio and shear-span ratio are the most consistent predictors of degradation, while detailing around openings controls post-peak stability. Modern finite-element, strut-and-tie and performance-based design studies improve prediction, but uncertainties remain for irregular openings, low-aspect-ratio walls, high axial load, cyclic degradation and post-installed penetrations. The paper concludes that safe design requires configuration-specific assessment rather than simple gross-area reduction, and it recommends integrated experimental databases, validated nonlinear models and practical detailing rules for resilient walls with openings. It also emphasizes practical evaluation of existing buildings where new openings are added after construction without original seismic design intent [2].

Keywords
Reinforced concrete shear wall; opening configuration; seismic performance; stiffness degradation; ductility; finite-element modelling; meta-analysis

1. Introduction

RC shear walls are widely used because they provide large in-plane stiffness, high lateral strength and effective drift control under wind and earthquake actions. In a building structural system, walls attract lateral forces in proportion to their stiffness and transmit overturning moments and shear forces to the foundation through flexural compression, tensile reinforcement and diagonal compression fields [4]. A solid wall with adequate boundary elements can exhibit stable flexural yielding, distributed cracking and considerable energy dissipation. However, the actual wall in a building is rarely perfectly solid. Functional requirements introduce door openings, window bands, elevator lobby passages, pipe shafts and ventilation penetrations. The structural problem is therefore not only to estimate the lost concrete area, but to understand how interrupted load paths redistribute forces around the void and change the interaction between flexure, shear and axial compression [5].

Past work establishes that wall aspect ratio, axial-load level, longitudinal reinforcement, transverse reinforcement, boundary confinement and web reinforcement govern the response of solid RC walls. Openings add further variables: opening area ratio, height-to-width ratio, vertical and horizontal eccentricity, alignment over stories, distance from boundary elements and detailing at the corners. These variables interact with global slenderness. In slender walls, openings influence neutral-axis depth, curvature demand and coupling action. In squat walls, they can destroy diagonal struts, encourage sliding shear and shift damage toward the ligament between the opening and the boundary. Consequently, the same opening percentage may have different structural meaning in a tall flexural wall and in a low-rise squat wall [6].

1.1 Opening configurations and performance indicators

Opening configuration describes the geometry and arrangement of voids within the wall panel. The most common configurations are central rectangular openings, edge or door-type openings, window-type openings located above floor level, vertically aligned openings forming coupled wall piers, staggered openings, multiple small service openings and post-construction cut-outs. Each configuration creates different load-transfer mechanisms [7]. A central opening usually forms two side piers and upper and lower spandrels; a side opening weakens one boundary region and produces torsion-like eccentric stress flow; staggered openings generate discontinuous pier lines and concentrate shear in short ligaments. Rounded or chamfered corners reduce stress concentration, while sharp rectangular corners commonly initiate diagonal cracking [8].

The performance indices used in past studies include initial stiffness, peak lateral strength, ultimate drift, ductility ratio, pinching of hysteresis loops, equivalent viscous damping, energy dissipation, residual displacement, crack width and damage distribution. Most experimental studies show an early reduction in initial stiffness compared with solid reference walls, but the magnitude depends strongly on the position and area of the opening. Centrally located small openings may reduce strength less than expected when boundary elements remain intact and reinforcement is properly anchored around the perimeter. By contrast, large door openings near wall edges often reduce lateral capacity substantially because one compression toe or tension boundary is weakened. Therefore, configuration must be treated as a structural design variable rather than an architectural afterthought [9].

1.2 Need, scope and objectives of the review

The need for a review and meta-analytic interpretation arises because individual investigations often focus on one geometry, scale, loading history or modelling approach. Some studies test low-rise squat walls, others examine slender high-rise walls or coupled walls, and many numerical papers vary only one parameter while holding material and detailing assumptions constant. Design codes provide general rules for boundary elements, shear reinforcement, coupling beams and discontinuities, but they do not always give explicit guidance for irregular openings or post-installed penetrations. Practitioners therefore require a synthesized account of past work that identifies robust conclusions, inconsistent findings and research gaps [10].

This paper reviews past experimental, analytical, numerical and code-oriented studies on RC shear walls with openings. It focuses on structural performance rather than architectural classification, and it interprets the literature in paragraph form as a narrative meta-analysis. The objectives are to explain observed mechanisms, compare trends across opening configurations, summarize methodology used in past work, critically evaluate limitations and present design-oriented conclusions [11]. The scope includes conventional cast-in-place RC walls, squat and slender walls, coupled wall behaviour, strut-and-tie interpretations and nonlinear finite-element modelling. Strengthening and advanced materials are discussed only when they clarify the response of openings or the rehabilitation of deficient configurations. The review is intended to support academic comparison as well as preliminary engineering judgement [12].

2. Survey of Past Work and Meta-Analytic Synthesis

Early research on RC shear walls concentrated on solid wall behaviour because walls were considered stiff vertical cantilevers governed by flexure in tall buildings and by shear in low-rise structures. The classic studies of reinforced concrete members and wall tests developed the foundation for understanding cracking, yielding, confinement and cyclic degradation. These investigations clarified that a well-detailed wall can dissipate energy through stable flexural plasticity, while inadequate web reinforcement or insufficient boundary confinement may lead to diagonal tension, web crushing, sliding or brittle compression failure. When openings were introduced into this framework, researchers recognized that the wall no longer behaves as a single homogeneous panel; instead, piers and spandrels act together through local force transfer [13].

The first major trend in past work concerns the influence of opening area ratio. Experimental and numerical studies consistently report that increasing the opening area reduces initial stiffness and lateral strength. The reduction is not linear because the location of removed concrete controls whether the principal compression strut, boundary compression zone or flexural tension field is interrupted. For small central openings, the wall may develop alternative diagonal struts around the void and retain a significant portion of strength. For large openings, particularly where the opening height extends through a major part of the wall, the remaining side piers behave like separate vertical members connected by short coupling beams. In such cases, failure may occur through shear cracking in spandrels, flexural yielding at pier bases, diagonal compression at opening corners or bond deterioration of bars crossing the disturbed region [14].

A second trend concerns opening location. Centrally located openings are generally less damaging than openings near edges when the wall is symmetric and boundary elements remain continuous. A central opening divides load paths almost equally into two piers, allowing a more balanced distribution of compression and tension. Edge openings, door-type openings and eccentric windows create unsymmetrical stiffness and force demand. They can reduce the effectiveness of one boundary element, intensify compression at the opposite toe and cause torsional or out-of-plane secondary effects if the wall is part of a three-dimensional core. Past cyclic tests show that cracks tend to initiate at re-entrant corners, then propagate diagonally toward the base or boundary, demonstrating the importance of local reinforcement detailing rather than only global strength calculation [15].

The third trend is the role of aspect ratio and shear-span ratio. Slender walls with openings often display flexure-dominated response if the piers are adequately reinforced and the coupling beams can yield in a ductile manner. In these walls, openings influence curvature distribution, neutral axis shift and coupling force [16]. The principal performance concern becomes deformation capacity and confinement of compression regions. Squat walls, however, rely strongly on diagonal compression struts. Openings in squat walls directly interrupt the strut-and-tie mechanism, making the response sensitive to diagonal reinforcement, horizontal web reinforcement and the remaining ligament dimensions. Tests on squat walls with openings often show pinched hysteresis, rapid stiffness degradation and brittle shear damage unless special detailing is provided [17].

A fourth issue is the number and arrangement of openings. Multiple small openings do not necessarily behave the same as one large opening of equal total area. If openings are aligned vertically, they may form continuous piers and coupling beams, a configuration similar to coupled shear walls [18]. The coupling beams can act as fuse elements when diagonally reinforced, protecting the piers and improving energy dissipation. If openings are staggered, however, the vertical load path becomes discontinuous; the wall develops irregular stress trajectories and localized damage in short concrete ligaments between adjacent openings. Numerical studies frequently demonstrate high principal tensile stresses at offset corners and high shear demand in narrow spandrels. Therefore, regularity and alignment often matter as much as total opening percentage [19].

Past analytical work has used equivalent frame models, wide-column models, strut-and-tie models, continuum finite-element models and fiber-based nonlinear wall elements. Equivalent frame models are attractive for design because they convert a perforated wall into piers and coupling beams with effective stiffness properties. Their limitation is that they require careful calibration of member lengths, rigid end zones and shear deformations. Strut-and-tie models provide useful insight for squat walls and deep spandrels because they represent diagonal compression and tension ties around openings. However, they may oversimplify cyclic degradation and damage spreading. Nonlinear finite-element models can capture cracking, crushing, bar yielding, bond-slip and stress concentration, but their predictions depend strongly on material constitutive laws, mesh size, tension stiffening, shear retention and boundary conditions [20].

Several researchers have investigated reinforcement around openings. The general finding is that additional horizontal, vertical and diagonal bars at the opening boundary can delay cracking, control crack width and improve post-peak response. Diagonal reinforcement at corners is particularly beneficial because it crosses likely diagonal tension paths. Closed stirrups or boundary-type confinement around larger openings can prevent premature concrete spalling and bar buckling. Nevertheless, reinforcement is effective only if it is properly anchored beyond the disturbed region. Short development lengths, congestion at corners and discontinuity of boundary longitudinal bars may reduce the benefit. Past work therefore supports performance-based detailing where the opening perimeter is treated as a local discontinuity region requiring dedicated force transfer [21].

Another group of studies evaluates opening shape. Rectangular openings dominate practice, but square, circular, arched and slot openings have been examined numerically and, to a smaller extent, experimentally. The major conclusion is that sharp re-entrant corners amplify tensile stress and create crack triggers, whereas rounded corners distribute stress more smoothly. However, a circular opening may still be harmful if it lies in the main diagonal compression path or near a boundary element [22]. Horizontal slots can severely reduce shear transfer because they cut across diagonal struts, while tall vertical openings may produce slender wall piers with high flexural demand. Shape is therefore secondary to force-path interruption, but corner geometry is important for serviceability and crack control. Researchers also note that construction tolerances and reinforcement placement around non-rectangular openings can affect performance, meaning that theoretical stress reduction from rounded corners should be supported by practical detailing [23].

The literature on coupled walls is directly relevant to walls with vertically aligned openings. In a coupled wall, two or more wall piers are connected by beams over openings. Under lateral loading, coupling beams transfer shear and create axial tension-compression couples in the piers, increasing overturning resistance. Properly detailed coupling beams can yield and dissipate energy, but poorly detailed beams may fail in shear and cause rapid loss of coupling. Diagonal reinforcement has been shown to improve coupling-beam behaviour under severe cyclic loading. This body of research explains why a wall with aligned door openings may perform better than an irregular perforated wall, provided the piers and coupling beams are deliberately designed rather than accidentally formed by architectural voids [23].

Research on high-rise core walls adds another dimension. Core walls often contain openings for elevators, doors and services, and they are subjected to high axial load, biaxial bending and torsion. Past studies show that high axial compression can increase initial strength but reduce ductility by accelerating crushing at boundary zones and opening corners. When openings are eccentric in a core, load distribution among webs changes, and coupling beams may experience complex shear and flexure. Three-dimensional finite-element and macro-model studies indicate that simplified two-dimensional analysis may miss redistribution through flanges and perpendicular walls. Consequently, the structural performance of openings in core walls must be assessed in the context of the full wall system [24].

Post-construction openings are a recurring concern in existing buildings. Cutting a new door or service penetration through a designed wall removes reinforcement, damages concrete, and changes stiffness after construction. Past rehabilitation studies propose steel plates, fiber-reinforced polymer sheets, additional RC frames, shotcrete jackets and steel collars around openings. Strengthening can recover part of the lost capacity, but the effectiveness depends on mechanical anchorage, compatibility with existing concrete, fire protection, durability and constructability. Research also shows that strengthening should not only replace removed area; it must restore a continuous force path and prevent crack concentration at the corners [25].

Meta-analytic comparison of past work reveals several consistent patterns. First, opening area ratio is a primary but incomplete predictor of performance loss. Second, eccentric openings are more damaging than symmetric openings of similar size. Third, the greatest damage usually occurs at re-entrant corners, narrow ligaments, spandrel ends and boundary zones adjacent to openings. Fourth, ductile response is possible when piers, coupling beams and opening perimeters are detailed for compatible deformation [25]. Fifth, finite-element models can reproduce trends but require validation against cyclic tests. Sixth, code provisions remain conservative for regular configurations and less explicit for irregular or post-installed openings. These patterns indicate that configuration-specific design is more rational than applying a uniform reduction factor to gross wall properties. The synthesis also indicates that service openings should be coordinated with structural modelling from the earliest design stage, because late relocation of openings can convert an otherwise ductile wall into a discontinuity-controlled element with little warning in simplified analysis. This finding is especially relevant for hospital, hotel and apartment buildings where service routes frequently change during construction [1].

3. Methodology

The methodology adopted for this review is a structured narrative meta-analysis of past work on RC shear walls with openings. Studies were conceptually grouped according to wall aspect ratio, opening area ratio, opening location, number of openings, loading type and modelling approach. Experimental papers were interpreted with priority because they provide direct evidence of cracking, hysteresis, stiffness degradation and failure modes. Analytical and numerical studies were then used to explain mechanisms and extend parameter ranges beyond those tested in laboratories. Standards and design guides were considered to relate research observations to practice. Instead of statistically pooling raw data, which are often unavailable and inconsistent in specimen scale and reinforcement details, this review synthesizes repeated trends across the literature [5].

For performance comparison, the main response measures were lateral load capacity, initial and secant stiffness, yield and ultimate drift, ductility, energy dissipation, failure mode and damage localization. Opening variables were interpreted as structural descriptors: area ratio described the amount of removed wall, eccentricity described disturbance of symmetry, alignment described whether the wall behaved as a coupled system, and ligament dimension described the remaining force-transfer path. The review also considered the influence of axial load, boundary confinement, web reinforcement and reinforcement around openings because these parameters modify the effect of geometry. Studies with solid reference walls were especially useful because they allowed relative comparison of perforated and unperforated behaviour [6].

The synthesis was developed in three stages. First, findings were extracted as qualitative cause-and-effect statements, such as whether increasing opening size reduced strength or whether diagonal bars improved crack control. Second, these statements were compared across experimental, finite-element and code-based sources to identify agreement or contradiction. Third, the implications were organized into design-oriented themes: load-path interruption, local stress concentration, coupling action, stiffness degradation and detailing requirements. This approach is appropriate for a review paper focused on past work because the literature includes varied specimen sizes, reinforcement ratios, concrete strengths, loading histories and boundary conditions. The limitation is that exact numerical prediction is not provided; instead, the paper identifies robust patterns and gaps that should guide future database development and model calibration [11]. A quality appraisal step was also used while interpreting the literature. Greater weight was assigned to studies that reported specimen geometry, reinforcement details, concrete strength, axial-load ratio, loading protocol and complete hysteretic response. Findings based only on unvalidated numerical models were used as supporting evidence rather than primary evidence. This procedure reduces the risk of treating isolated parametric results as general rules and allows conclusions to be linked to repeatable physical mechanisms such as strut interruption, corner tension and coupling-beam yielding. The methodology further distinguishes between new-design openings and openings introduced in existing structures. New openings can be accommodated by planned reinforcement continuity, whereas post-installed openings require assessment of cut bars, damaged concrete, redistribution of stiffness and the need for external strengthening. This distinction is maintained throughout the interpretation so that design recommendations are not confused with retrofit decisions [23].

4. Critical Analysis of Past Work

Although past work has significantly improved understanding of RC shear walls with openings, several limitations remain. Many experimental programs use small-scale specimens, simplified boundary conditions and constant axial load, whereas real walls experience multi-story continuity, floor-slab restraint, variable gravity load, biaxial bending and interaction with frames. Scale effects can alter crack width, bond behaviour, aggregate interlock and bar buckling. Therefore, conclusions from one-third or one-half scale tests should be applied cautiously to full-size walls unless similitude and reinforcement detailing are carefully addressed. In addition, many tests use monotonic or quasi-static cyclic loading; fewer studies reproduce long-duration earthquake sequences, aftershocks or combined vertical and lateral excitation [2].

Another weakness is the uneven coverage of opening configurations. Central rectangular openings are well represented, but irregular, staggered, circular, large door-type and post-installed openings are less systematically studied. Real buildings often contain combinations of openings over several stories, with architectural changes from floor to floor. Such vertical irregularity can produce weak stories or unintended transfer regions. Past research tends to vary one parameter at a time, while actual design involves simultaneous variation of opening size, location, reinforcement and axial load. This limits the ability to develop universal design equations. It also explains why code guidance is typically general and conservative rather than configuration-specific [28].

Critical review of numerical research shows both progress and risk. Nonlinear finite-element modelling can reveal principal stress flow, crack concentration and redistribution around openings, but model results may appear precise while being highly sensitive to assumptions. Concrete damage plasticity parameters, shear retention factors, bond-slip laws, tension stiffening and mesh density can change predicted peak strength and post-peak ductility. Some parametric studies validate the model using only a solid wall or a single perforated specimen, then extrapolate to many opening shapes. Such extrapolation may be unreliable for configurations with severe stress concentration or brittle shear. Robust validation should include multiple opening ratios, eccentricity levels and cyclic degradation histories [22].

There is also a gap between research indicators and design decisions. Researchers often report peak load, ductility and energy dissipation, but practicing engineers need clear detailing rules, acceptance criteria, drift limits and repairability expectations. For example, an opening configuration may retain adequate peak strength but suffer severe residual cracking, large permanent drift or difficult repair after an earthquake. Similarly, a strengthened opening may restore stiffness but attract greater force to adjacent elements. Performance-based design should therefore evaluate not only strength but also damage concentration, residual deformation and replaceability of yielding components such as coupling beams.

Another critical issue is that many conclusions are expressed as percentage reductions in capacity without clearly separating stiffness, strength and deformation effects [11]. A wall may lose large initial stiffness but retain acceptable ultimate strength, or it may show modest strength loss but experience abrupt post-peak degradation. These distinctions matter for serviceability, drift control and collapse prevention. Some past studies also compare walls with different reinforcement layouts, making it difficult to isolate the influence of the opening itself. A rigorous evaluation should compare perforated specimens with matched solid controls and should report normalized indices such as strength ratio, stiffness ratio, drift ratio and dissipated energy ratio. Without such normalization, the literature may appear contradictory even when the underlying mechanisms are consistent [29].

Past studies sometimes treat reinforcement around openings as a generic addition without quantifying development length, anchorage, congestion and constructability. In practice, placing diagonal bars, closed stirrups and boundary cages around small openings can be difficult, especially where mechanical and electrical services occupy the same space. Poor anchorage may cause reinforcement to slip before it develops intended resistance. Research should therefore integrate detailing feasibility with structural performance. Full-scale tests and field-oriented studies on constructible reinforcement layouts would be more valuable than idealized arrangements that cannot be easily implemented on site [5].

A final issue is the need for comprehensive databases. A true statistical meta-analysis requires consistent data for geometry, material properties, reinforcement ratios, axial load, loading protocol, failure mode and response curves. Existing information is scattered across papers and often lacks raw hysteresis data or complete reinforcement details. Without open databases, design models remain dependent on limited calibration sets. The literature supports the conclusion that opening area, eccentricity, aspect ratio and detailing quality dominate performance, but the exact threshold between acceptable and unsafe configurations is still uncertain for many cases [25]. Future work should combine experimental databases, machine-learning-assisted parameter screening and mechanics-based models so that prediction remains both accurate and interpretable. Research should also report negative or low-performance configurations, because failed or poorly performing specimens often reveal the most important boundary conditions for safe design. Such evidence is essential for defining practical limits on opening size, eccentricity and minimum ligament dimensions, and for avoiding unconservative extrapolation from regular laboratory specimens to irregular building cores [3].

5. Discussion

The reviewed studies collectively show that the structural performance of RC shear walls with openings is governed by the continuity of force paths. A solid wall carries lateral load through combined flexural compression-tension and diagonal shear transfer. An opening interrupts these paths and forces stresses to move around corners, through narrow ligaments and into adjacent piers and spandrels. If the remaining elements are proportioned and detailed as a deliberate coupled system, the wall can maintain adequate strength and ductility. If the opening is treated merely as removed area, brittle local damage and unexpected stiffness loss can occur [8].

For design, the most important implication is that opening configuration should be evaluated early in architectural planning. Symmetric and vertically aligned openings are generally preferable because they create regular piers and coupling beams. Eccentric and staggered openings require more rigorous analysis and detailing, especially in seismic regions. The opening perimeter should be considered a discontinuity region where diagonal tensile stresses and compression struts must be anchored. Additional reinforcement at corners, confinement of narrow piers, adequate spandrel design and protection of boundary elements are essential. Where openings are unavoidable near edges, designers should check whether a boundary element has been weakened and whether alternative load paths exist [17].

The discussion also indicates that no single modelling method is sufficient for all cases. Equivalent frame models are efficient for regular openings and preliminary design. Strut-and-tie models are powerful for squat walls and deep transfer regions. Nonlinear finite-element models are useful for irregular configurations, high axial load and performance assessment, but they must be validated and interpreted with engineering judgment. Code-based minimum reinforcement should be viewed as a baseline, not as proof of adequate seismic performance when openings create severe discontinuities [16].

In existing buildings, new openings should be avoided unless a structural assessment confirms sufficient residual capacity. If cutting is necessary, strengthening should restore continuity through steel frames, RC jackets, FRP systems or other anchored mechanisms. The strengthening design should consider stiffness compatibility, load redistribution and durability. Overall, past work supports a shift from area-based rules to mechanism-based design. The wall with openings should be seen as an assembly of interacting piers, spandrels, boundary zones and discontinuity regions, each requiring compatible strength and deformation capacity [18]. For seismic design, this means that capacity design principles should be extended to the perforated wall system: ductile components should yield in a controlled manner, brittle shear and anchorage failures should be prevented, and local strengthening should not create an undesirable weak zone elsewhere. Serviceability should also be checked because cracks at opening corners may affect durability and occupant confidence even before ultimate strength is reached. A balanced design therefore combines global checks of drift and base shear with local checks of corner cracking, anchorage, confinement and deformation compatibility among the remaining wall segments. Such integration is the clearest lesson from the accumulated body of past work [22].

6. Conclusion

This review paper examined past work on the structural performance of reinforced concrete shear walls with different opening configurations. The meta-analytic synthesis shows that openings reduce stiffness and strength by interrupting diagonal struts, flexural stress fields and boundary continuity, but the severity depends on size, position, alignment, wall aspect ratio, axial load and detailing. Small central openings may be accommodated with moderate performance loss, while large, eccentric, staggered or multiple openings can cause severe stress concentration and transform the wall into an irregular coupled system. The most vulnerable zones are opening corners, narrow ligaments, spandrel ends and weakened boundary regions [11].

Past experimental and numerical studies agree that proper reinforcement around openings, adequate anchorage, confined boundary elements and ductile coupling beams can significantly improve performance. However, research gaps remain for full-scale irregular openings, high axial load, post-installed penetrations, cyclic degradation and three-dimensional core wall behaviour. Design practice should therefore avoid simple gross-area reduction and instead use configuration-specific, mechanism-based assessment. Future research should develop open experimental databases, validated nonlinear models and practical detailing provisions so that RC shear walls with necessary openings can achieve reliable strength, ductility, energy dissipation and repairable seismic performance [18]. The most useful future provisions will connect simple design checks with experimentally verified mechanisms, enabling engineers to approve, modify or reject opening layouts before they compromise the intended lateral-load resisting system. Thus, coordinated architectural planning, robust detailing and validated analysis remain the central requirements for safe perforated RC shear walls in seismic and wind-resistant construction [29].

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