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NONLINEAR BEHAVIOR OF REINFORCED CONCRETE SHEAR WALLS UNDER COMBINED LOADING: A COMPARATIVE REVIEW OF ACI 318M-25 AND EUROCODE 8 PROVISIONS

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Abstract

Reinforced concrete (RC) shear walls are the primary lateral load-resisting system in mid- and high-rise buildings. Increasing architectural complexity now subjects many of these walls to combined axial force, bending moment, shear, and torsion acting simultaneously, producing a highly nonlinear response governed by concrete cracking, reinforcement yielding, stiffness degradation, and progressive damage. This paper reviews experimental and numerical studies published between 2004 and 2025 on the nonlinear behavior of RC shear walls and compares how the American code ACI 318M-25 and the European code Eurocode 8 (together with Eurocode 2) treat the key design parameters that govern this behavior, namely effective cracked-section stiffness, longitudinal and transverse reinforcement ratios, inter-story drift limits, base-shear calculation, and plastic-hinge location. The review shows that both codes rely on simplified, largely empirical stiffness-reduction factors, about 65% for ACI 318M versus 50% for Eurocode 8-Part 1, that do not capture the true, load-dependent nature of cracked-section stiffness; that reinforcement ratio limits differ substantially between the two codes; and that neither code, nor the related Turkish seismic code, provides a closed-form expression for plastic-hinge length as a function of wall geometry and reinforcement ratio. Persistent gaps are identified regarding FRP-reinforced walls, non-rectangular wall shapes (U, L, T, coupled and perforated walls), and boundary-element/stiffness interaction, and directions for future analytical and design-oriented research are proposed.

Keywords: RC shear walls; nonlinear behavior; ACI 318M-25; Eurocode 8; effective stiffness; plastic hinge; seismic design; finite element modeling

1. Introduction

RC shear walls are widely relied upon by structural engineers to resist lateral actions on buildings, whether induced by earthquakes, wind, soil pressure, or fluid loads, and their presence strongly influences a building's overall strength, stiffness, and deformation characteristics (Fethi & Orakcal, 2014). As the applied forces increase, wall behavior transitions from linear to nonlinear, governed by concrete cracking and reinforcement yielding, and engineers continue to face a shortage of validated resources for simulating this nonlinear response or for predicting damage such as concrete crack width or spalling at inter-story drift levels of interest.

The rapid evolution of architectural practice, combined with the trend toward irregular, slender, high-rise geometries, means that structural walls are no longer subjected to the simple loading patterns assumed by traditional analysis; they now operate under combined and simultaneous load effects. Modern buildings frequently contain complex wall configurations — asymmetric layouts and irregularly placed openings driven by architectural and functional requirements — that are expected to produce significant variation in local damage patterns and ductility demand, and that require sophisticated modeling (Birely et al., 2008; Kelly, 2004).

Nonlinear concrete behavior can be captured using finite element methods, but the complexity stems from the nonlinear stress–strain relationship of concrete under strain softening, non-uniform stiffness reduction, and progressive cracking resulting from tensile stresses and strains, bond–slip between concrete and reinforcement, aggregate interlock, and time-dependent effects such as creep and shrinkage (Chaudhari & Chakrabarti, 2012). Modeling techniques have evolved substantially over the past two decades, moving from static idealizations toward fully nonlinear dynamic modeling (Hasanzadeh, Vatin, & Kharun, 2025).

RC shear walls are used efficiently both in the seismic design of new buildings and in the retrofit of existing structures; simulating their nonlinear response under combined loading, particularly severe seismic loading, remains a critically important engineering problem, and detailed finite-element-based nonlinear dynamic analysis requires extensive computation and precise solution techniques (Kotronis, Ragueneau, & Mazars, 2005). Many existing buildings with RC shear walls located in high-seismicity regions require seismic assessment through re-analysis and re-design to satisfy modern code requirements, and nonlinear static and dynamic analyses are essential to evaluate their expected seismic performance (Çavdar & Bayraktar, 2018).

Because no national structural design code currently exists in Libya, the American (ACI) and European (Eurocode) codes are the two most widely used references in the Libyan engineering environment. Accurate prediction of the strength and deformation capacity of RC shear walls is therefore essential, and designers require precise knowledge of nonlinear static or dynamic modeling to more realistically represent wall behavior within the overall structural system, given that wall response under combined bending, shear, and axial force directly governs structural safety. This motivates a focused review of the latest editions of both codes: ACI 318M-25 and Eurocode 8 (2023 update) — with respect to their treatment of RC-wall nonlinear behavior.

The objective of this review is threefold: (i) to synthesize the experimental and analytical literature (2004–2025) on the nonlinear behavior of RC shear walls under combined loading; (ii) to compare, parameter by parameter, how ACI 318M-25 and Eurocode 8/2 quantify effective stiffness, reinforcement limits, drift, and plastic-hinge behavior; and (iii) to identify the research gaps that a future combined analytical–numerical study, informed by the literature reviewed here, would need to address.

2. Comparative Code Provisions: ACI 318M-25 versus Eurocode 8/Eurocode 2

Table 1 summarizes the principal differences between the two codes for parameters that directly govern the nonlinear response of RC shear walls. Eurocode 8 (2004) classifies seismic analysis methods into static procedures (equivalent lateral force, nonlinear static pushover) and dynamic procedures (response spectrum, time-history), broadly paralleling the classification used by ACI-referenced standards (ASCE 7).

Parameter	ACI 318M-25	Eurocode 8 / Eurocode 2
Seismic analysis methods	Equivalent lateral static force; response spectrum; nonlinear time-history	Equivalent static method; nonlinear static pushover; response spectrum; time-history
Basis of base-shear calculation	Seismic response coefficient and effective seismic weight of the building	Design spectrum at fundamental period T1, total building mass, and a correction factor
Allowable inter-story drift	Up to 2.5% for multi-story RC buildings (ASCE7-16/ACI318-19)	1% (brittle non-structural elements), 1.5% (ductile), 2% (non-ductile) — EC8
Independent wall design requirement	—	Wall must resist ≥25% of the design base shear when acting with a moment-resisting frame system
Effective (cracked-section) stiffness reduction	Up to 65% reduction (effective stiffness ≈ 0.35 Ig)	EC8-Part1: 50% reduction (effective stiffness ≈ 0.50 Ig)
Minimum reinforcement ratio	≥ 0.0025 horizontal and vertical (ACI 318-19); no stated maximum	0.004 minimum (Eurocode 2)
Maximum longitudinal reinforcement ratio	Not explicitly specified	0.04 (Eurocode 2)
Plastic-hinge length/location formula	Not provided (approximate estimate: mid-height, used in some studies)	Not provided; the Turkish code (TBEC) also lacks this formula
FRP reinforcement provisions	Not covered	Not covered

Table 1. Comparative summary of ACI 318M-25 and Eurocode 8/Eurocode 2 provisions relevant to nonlinear RC shear-wall behavior.

Several observations follow directly from this comparison. First, the two codes disagree substantially on the base-shear formulation: ACI-based procedures anchor base shear to a seismic response coefficient and the effective seismic weight, whereas Eurocode 8 anchors it to the design spectral ordinate at the fundamental period, the total seismic mass, and a correction factor — a difference in both the governing equations and the input parameters that inevitably yields different demand estimates for a given building (Oussadou, 2021). Second, drift limits under Eurocode 8 are markedly more restrictive than under ACI 318-19/ASCE 7-16 for buildings with non-structural elements, which in turn affects the stiffness and reinforcement required to satisfy serviceability limit states (Oussadou, 2021).

3. Thematic Literature Review

3.1 Finite element and numerical modeling approaches

Kelly (2004) showed that ultimate strength and hysteretic characteristics of a range of RC shear walls, with and without openings, could be predicted within about 10% of experimental results using nonlinear static and dynamic finite element analysis, by developing a model grounded in structural mechanics principles calibrated against experimental data. Kotronis, Ragueneau, and Mazars (2005) modeled two prototype RC walls under the European (EC8) and French (PS92) codes using a damage-mechanics and plasticity framework combined with classical Bernoulli multilayered beam theory; they found that EC8 concentrates damage at the wall base whereas PS92 distributes it along the wall height, and that distributing the load-transfer region over the full wall height reduces the required reinforcement quantity, while also revealing a discrepancy between numerical and experimental axial-force results.

Chaudhari and Chakrabarti (2012) compared smeared-crack modeling against concrete damage-plasticity modeling in ABAQUS, obtaining maximum stresses of approximately 29.39 MPa and 32.32 MPa respectively against an expected value of about 30 MPa, and showed that in the damage-plasticity approach mesh size plays a critical role, with finer meshes converging toward the target stress. Al-Mafalani (2014) developed a finite-element shear-wall model in ABAQUS 6.5-1 to examine the influence of boundary (hidden) column reinforcement ratio and thickness, finding a modest nonlinear strength gain with increased reinforcement ratio and a 47% strength increase when boundary-column thickness was quadrupled relative to the wall thickness; the study recommended further work on walls with openings, taller wall assemblies, and varying wall length. Fethi and Orakcal (2014) proposed a new finite-element formulation, implemented in MATLAB with a drift-controlled nonlinear solution strategy, that gave reasonably accurate predictions of lateral load capacity, stiffness degradation, hysteretic shape, residual plastic displacement, ductility, and pinching behavior, as well as the nonlinear shear deformations developing within the plastic-hinge region. Foroughi and Yuksel (2025) used ANSYS Mechanical with APDL command scripting to perform nonlinear dynamic analysis of an RC shear wall under seismic loading, finding that the linear response-spectrum method (RSM) over-predicted peak displacement (about 5 cm) relative to the nonlinear dynamic analysis (about 2 cm), a difference attributed mainly to the built-in safety margin of RSM.

3.2 Experimental studies of seismic behavior and damage mechanisms

Birely et al. (2008), testing planar RC walls at the NEES-UIUC MUST-SIM facility on specimens representing the bottom three stories of a ten-story prototype building, showed that damage initiates at the wall–foundation connection, indicating that connection detailing directly affects seismic performance; that reduced effective height significantly increases drift and causes a sudden loss of lateral strength; and that damage patterns (originating either from the interior and spreading outward, or beginning uniformly at the wall boundaries near a splice region) directly reduce drift capacity. Moment, shear, and axial load were applied at the wall top to represent the effect of the upper stories, and the moment-to-shear ratio was varied across tests to better capture the combined influence of dynamic loading and stiffness variation on seismic performance.

Panagiotou (2008) developed a displacement-based seismic design method for wall buildings for use within performance-based design, validated through shake-table testing of a full-scale seven-story RC wall specimen at the University of California, San Diego, and also quantified the probability of collapse associated with recorded ground motions. The study introduced the concept of a dual plastic-hinge design to improve the performance of tall core-wall buildings and demonstrated excellent performance even though the reinforcement quantity was only 50% of that required by the American code. Çavdar and Bayraktar (2018) evaluated an eight-story RC shear-wall building that collapsed in the 2003 Bingöl earthquake in Turkey, applying nonlinear static pushover and nonlinear time-history analysis per the Turkish code; nonlinear static analysis indicated the building satisfied life-safety criteria, whereas nonlinear dynamic analysis indicated actual collapse, with major damage and plastic hinges concentrated in the upper stories — illustrating that performance level in earthquake engineering is intrinsically tied to the damage state predicted by the analysis method used.

3.3 Effective (cracked-section) stiffness of shear walls

Multiple studies converge on the finding that the effective stiffness of a cracked RC wall section is not a fixed value, contrary to the single reduction factors prescribed by codes (approximately 0.35 for ACI, 0.50 for Eurocode), but rather a complex function of axial load level, concrete strength, and transverse and longitudinal reinforcement quantities (Forough & Yüksel, 2021; Foroughi & Yuksel, 2025). Forough and Yüksel (2020) showed that changes in transverse and longitudinal reinforcement and in axial load level significantly affect moment–curvature response, lateral force behavior, lateral peak displacement, and displacement ductility of high-ductility shear walls designed per the Turkish seismic code (TBEC 2018); moment capacity and curvature ductility increased as transverse reinforcement spacing decreased, while yield moment remained nearly constant even as ultimate moment, yield curvature, ultimate curvature, and curvature-ductility values increased with larger transverse bar diameters.

Forough and Yüksel (2021) analytically derived effective cracked-section stiffness for shear walls designed per TBEC (2018), ACI 318 (2014), ASCE/SEI 41 (2017), and Eurocode 8 (2005), confirming that reducing stirrup spacing increases both moment capacity and ductility, and that none of the American, European, or Turkish codes account for the confinement effect of boundary elements or the interaction between concrete strength and axial load in their fixed stiffness-reduction factors. Hasanzadeh, Vatin, and Kharun (2025), through a parametric study of 135 RC shear-wall models with varying transverse and longitudinal reinforcement ratios, concrete compressive strength, and axial load, proposed a comprehensive closed-form equation for the effective stiffness of high-ductility shear walls that explicitly accounts for nonlinear behavior, directly addressing the gap left by the fixed 0.35/0.50 factors used in ACI and Eurocode 8-Part 1, respectively.

3.4 Reinforcement detailing, boundary elements, plastic hinges, and ductility

The longitudinal and transverse reinforcement of an RC wall governs its load capacity, ductility, and moment–curvature response (Forough & Yüksel, 2020). Eurocode 2 sets a minimum reinforcement ratio of 0.004 and a maximum longitudinal ratio of 0.04 for shear walls, whereas ACI 318-19 requires horizontal and vertical ratios greater than 0.0025 without specifying an upper bound; this generally makes the Eurocode design more economical in reinforcement quantity (Oussadou, 2021). Hassan, Anwar, Norachan, and Najam (2018), designing a 40-story building in seismically active Manila, Philippines to three different codes using ETABS, found that Eurocode reinforcement was less than half the ACI requirement and saved roughly 185 tonnes of longitudinal steel relative to the American and British codes, while all three codes produced acceptable drift and deformation performance under the design earthquake.

Regarding plastic hinges — the localized regions where nonlinear (plastic) deformation concentrates once reinforcement yields and concrete cracks or crushes, and which dissipate seismic energy by allowing wall rotation and deformation without sudden collapse — Aydin, Bayrak, Maali, Kılıç, and Alcan (2020) note that neither the American (ACI 318M-19), European, nor Turkish codes provide a mathematical relationship for locating the plastic hinge as a function of wall length and reinforcement ratio; some researchers instead use an approximate assumption that the hinge forms at wall mid-height. The same study also highlights that none of the three codes adequately address non-rectangular wall geometries (U-, L-, and T-shaped sections), open or hollow walls, or FRP reinforcement, and notes that while ACI applies a strength-reduction factor in shear-capacity calculations, the Turkish code explicitly defines a critical shear height with recommended reinforcement redistribution at that height, and both ACI and Eurocode account for a ductility (behavior) factor and moment of inertia.

3.5 Code comparison and design-economy studies

Oussadou (2021) compared ACI 318M-19 and Eurocode provisions for columns, shear walls, and slabs through a detailed cost analysis of a 50-story high-rise subjected to seismic and wind loads, finding that Eurocode 2 assigns concrete a higher elastic modulus (hence apparent stiffness) than ACI 318M-19, affecting reinforcement quantities and other seismic/wind design requirements; following Eurocode achieved substantial overall cost savings, particularly in low-to-moderate seismicity regions, leading the study to recommend Eurocode over ACI318-19/ASCE 7-16 for economy-driven designs. Aydin et al. (2020) similarly compared shear-wall design and behavior between the 2019 Turkish code, ACI 318M-19, and Eurocode 2, concluding that important gaps — the absence of a plastic-hinge-length formula, insufficient guidance for non-rectangular and perforated walls, and the omission of FRP reinforcement — persist across all three regulatory frameworks.

4. Discussion and Synthesis

Taken together, the reviewed studies indicate that the nonlinear response of RC shear walls under combined loading is governed by an interacting set of phenomena — progressive cracking, bond–slip, stiffness degradation, and reinforcement yielding — that neither ACI 318M-25 nor Eurocode 8/2 captures through more than a single, load-independent reduction factor for stiffness, and that neither code offers a rational basis for locating the plastic hinge. The two codes further diverge on base-shear computation, drift limits, and reinforcement-ratio bounds, which explains why parallel code-comparison studies (Oussadou, 2021; Hassan et al., 2018; Aydin et al., 2020) consistently report substantially different reinforcement quantities and overall cost outcomes for nominally identical buildings. Where the literature does offer closed-form alternatives — most notably the stiffness equations proposed by Forough and Yüksel (2021) and Hasanzadeh, Vatin, and Kharun (2025) — these are derived from a still-limited parametric space (predominantly high-ductility, rectangular, steel-reinforced walls) and have not been reconciled into a single expression applicable across the ACI and Eurocode design environments.

A secondary but recurring theme is the near-total absence, across all three regulatory frameworks reviewed (ACI, Eurocode, and the Turkish code), of provisions for FRP-reinforced walls and for non-rectangular or perforated wall geometries — despite the architectural trend toward exactly these configurations noted in the introduction. This represents both a code-development gap and a research opportunity.

5. Research Gaps and Future Directions

Based on the synthesis above, the following gaps warrant dedicated analytical and numerical investigation:

• A unified, physically based expression for the effective cracked-section stiffness of RC shear walls that reconciles the fixed ACI (≈0.35) and Eurocode 8 (≈0.50) reduction factors with the load- and reinforcement-dependent behavior documented in the literature.

• A closed-form relationship for plastic-hinge length/location as a function of wall length and longitudinal/transverse reinforcement ratio, applicable under both ACI and Eurocode design assumptions.

• Systematic treatment of combined axial force–shear–bending–torsion interaction under advanced nonlinear finite-element analysis (static pushover and dynamic time-history), extending beyond the mostly uniaxial or biaxial loading scenarios addressed in the studies reviewed here.

• Extension of current knowledge to non-rectangular (U, L, T), coupled, and perforated wall configurations, which remain inadequately covered by ACI, Eurocode, and the Turkish code alike.

• Evaluation of FRP longitudinal and transverse reinforcement in RC shear walls, an area not addressed by any of the three codes discussed.

• A mathematical framework capable of reconciling ACI 318M-25 and Eurocode 8 design outcomes for a given wall, to support engineers working — as in the Libyan context — without a dedicated national structural code.

6. Conclusion

This review has synthesized two decades of experimental and numerical research (2004–2025) on the nonlinear behavior of RC shear walls and has compared, provision by provision, how ACI 318M-25 and Eurocode 8/Eurocode 2 address the parameters that govern this behavior. The comparison shows persistent and consequential differences in base-shear computation, drift limits, reinforcement-ratio bounds, and — most critically — in the treatment of effective cracked-section stiffness and plastic-hinge location, where both codes rely on simplified, fixed coefficients rather than physically derived, load-dependent relationships. Closing these gaps, particularly through a unified stiffness expression and a rational plastic-hinge model validated against both codes' assumptions, would materially improve the accuracy of nonlinear seismic assessment of RC shear-wall buildings and would be of direct practical value in engineering environments, such as Libya's, that rely on both codes in the absence of a dedicated national standard.

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