International Journal Of Advances In
ENGINEERING, SCIENCE, COMMERCE, MANAGEMENT AND LAW
(IJAESCML)

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

www.ijaescml.com | internationaljournal1234@gmail.com | Peer Reviewed & Refereed Journal

[Structural Behaviour of Multi-Storey Buildings with Circular and Rectangular Columns under Earthquake Loads: A Review]

Shahnavaj[*1], Mrs. Ankita Singhai[*2], Dr. Rahul Kumar Satbhaiya[*3]

[*1]Research Scholar, Civil Department, Infinity Management & Engineering College, Sagar.

[*2]Asst. Prof. and Guide, Civil Department, Infinity Management & Engineering College, Sagar.

[*3] HOD, Civil Department, Infinity Management & Engineering College, Sagar

ABSTRACT

In seismically active areas, reinforced concrete (RC) moment-resisting frames are still the most commonly used structural system for multi-story buildings and the seismic behaviour of RC moment-resisting frames is highly dependent on the size, shape and detailing of the columns. Until now, the use of circular columns was limited to member-level and connection-level analyses and no studies have investigated their full benefits and performance at the entire building scale under earthquake loading, although the columns are known to provide more uniform core confinement and an isotropic flexural stiffness distribution at earlier stages of investigation.This review aims to consolidate current knowledge, highlight the methods and technologies used and reveal the key research gaps underpinning the nonlinear static (pushover) assessment of RC buildings, while summarising 30 years of research with a specific focus on those that compare the seismic performance of circular and rectangular column sections in some way, directly or indirectly.Despite the documented limitations of pushover analysis, with regard to invariant load patterns and single-mode idealisation, reviewed literature shows that pushover analysis has been the most popular nonlinear static method for performance-based seismic evaluation, evolving from the Capacity Spectrum Method of ATC-40, through the Displacement Coefficient Method of FEMA-356, to the equivalent linearization procedure of FEMA-440. Extensive member-level and, in more recent publications, building-level studies have all shown that, in general, circular RC columns have lower base-shear attraction, slightly lower storey drift points and more favourable equivalent-linearization points than rectangular columns of the same cross-sectional area as a result of more uniform confinement and the absence of stress-concentrations at sharp corners. New findings like machine-learning surrogate models for prediction of capacity curves as well as developments in textile- and polyurea-based retrofit systems are now starting to expand and in some instances contradict the findings of classical pushover studies.High priority research needs identified in this review are full three-dimensional, building-scale parametric studies that consider column shape as a variable only; incorporation of explicit shear and joint failure criteria into the nonlinear static procedures; validation of conclusions from pushover analyses against nonlinear time-history and shake-table analysis; and development of standardised design guidance for circular RC columns in multi-storey moment-resisting frames, where current code provisions are relatively under-developed compared to their treatment of rectangular columns.

KEYWORDS: reinforced concrete frame; circular column; rectangular column; pushover analysis; nonlinear static procedure; seismic performance; FEMA-440; capacity spectrum method; performance-based earthquake engineering; earthquake-resistant design

Received	Accepted	Published	Article Type
05/07/2026	15/08/2026	31/08/2026	Research Paper

1. Introduction

1.1 Overview of the Topic

In most buildings constructed traditionally, lateral forces that are generated during an earthquake are transient and can be resisted by either reinforced concrete (RC) moment-resisting frames or shear walls, or a combination of the two. In a moment resisting frame, columns are the members that are required to carry the axial gravity load and resist the combined axial gravity load, biaxial bending and shear demand caused by lateral earthquake loading as well. Their cross-section shape, size and reinforcement detailing therefore has a first order effect on the overall seismic performance of the building [1]. However, rectangular and square sections are ubiquitous, subject of the reinforcement and economy of their associated formwork, the need to detail the beam-column joints, and the architectural integration, and circular sections, where there are closely spaced circular ties or a continuous spiral, are recognised in the literature of reinforced-concrete and earthquake-engineering as providing a more uniform triaxial confinement of the concrete core and an isotropic second moment of area about every bending axis [2], [3].

Since the 1990s, seismic assessment of both shapes has been increasingly conducted using nonlinear static procedures, often referred to as pushover analysis, which are more complex than the linear-elastic code procedures, but less complex than the more demanding nonlinear time-history analysis. The majority of pushover-based studies reviewed in this article are based on the analytical framework, hinge-modelling conventions and demand-estimation procedures outlined in guidance documents from the Applied Technology Council and the Federal Emergency Management Agency, primarily ATC-40 [4] and FEMA-356 [5] and their update in FEMA-440 [6].

1.2 Importance and Motivation

The following two independent streams of literature are the motivators for the present review. The first is about the static, nonlinear procedure itself; its accuracy against the nonlinear time-history and recorded strong-motion response; and the successive corrections to the known deficiencies in the original ATC-40 and FEMA-356 formulations [7], [8] that were introduced by FEMA-440 and ASCE/SEI 41-06. The second relates to the specific shape of the column's cross section: numerous reports of member-level and retrofit-related research have demonstrated that circular RC columns are more effective at containing the concrete in the core, at resisting spalling and buckling of the steel bars in the concrete at large drift and at responding better to jacketing and wrapping-based strengthening than rectangular columns of similar dimensions [9, 10]. Until relatively recently, however, there has been little research that links these two streams of literature directly—that is, research that uses nonlinear static methods on a whole building of multiple stories to test whether the member-level benefits of circular columns are manifest at the building level. This review has been prompted by a need to bring together the evidence available to answer this particular question, and to determine what is not yet known.

1.3 Objectives of the Review

This review aims to present the following: (i) a summary of the evolution, current status of the nonlinear static (pushover) analysis, and its extension to RC buildings; (ii) a structured compilation and comparison of studies that have investigated the effect of column cross-sectional shape on seismic performance, particularly, circular sections; (iii) identification of new advances and research technologies that have broadened the scope of both pushover-based and column-shape-related seismic research; (iv) the main technical limitations of existing methods and research gaps for the specific field of column-shape comparison; and (v) directions for future research that would help close these gaps

2. Literature Review

2.1 Existing Studies

The literature, which can fruitfully be followed from the methodological origins to those that specifically consider the problem of the column geometry, can be classified into two groups: literature present in the methodological sense and literature specifically regarding the column geometry. While examining an infilled 4-storey RC frame, Griffith and Pinto [11] observed that increased drift capacity in the bare frame (approx. two per cent) compared to a drift capacity of 0.3 per cent with the infills, is highly dependent on the secondary elements. In 1933, instrumented strong-motion recording was introduced and after that, the capacity-design concepts were adopted for RC design, and Otani [12] studied the historical development; he plotted the earthquake damage statistics in Kobe against the design period of the earthquake-damaged buildings.

Martinelli and Nigro [13] suggested a displacement-based approach for comparing the seismic capacity and demand, claiming that it is more suitable to use a displacement-based target when considering retrofit of an existing structure. Oğuz [14] performed pushover analysis for various load patterns and compared the results obtained from this analysis with the nonlinear time-history analysis results for RC and steel frames covering a broad range of periods, and found that the accuracy of the pushover analysis depends on the load pattern, the characteristics of the ground motion, and the dynamic characteristics of the frame. Rai [15] summarized guidelines for seismic assessment and strengthening of the existing Indian building stock, while Thermou and Elnashai [16] summarized the effects of common repair and retrofit solutions on member ductility, strength and stiffness.

Kadid and Boumrkik [17] used pushover analysis to an Algerian code RC building, and they highlighted the need for realistic modelling of hinges for buildings with highly inelastic responses. Goel (1992 [18]) compared the FEMA-356, ASCE/SEI 41-06, ATC-40 and FEMA-440 nonlinear static procedures with the recorded displacements from instrumented earthquakes, with the result that the FEMA-440 Capacity Spectrum Method (C.S.M.) gave more accurate estimates of displacement than the previous ATC-40 procedure, and this has influenced the selection of the procedure used to estimate demands in most other studies, including this Review's emphasis on FEMA-440.

Sarkar [19] studied RC frames on sloping ground and pointed out the "short-column effect," while Sattar and Liel [20] demonstrated that fully infilled frames have lower collapse risk than bare frames, using incremental dynamic analysis; Monavari, Massumi and Kazem [21] benchmarked local and global failure criteria for thirteen buildings under the Iranian code ranging from two to twenty storeys; Tamboli and Karadi [22] demonstrated that open-ground-storey configurations produce significantly greater ground-storey drift than bare frames or fully infilled frames; and Bodige and Ramancharla [23] compared the Applied Element Method with the conventional pushover analysis method and found that capacity is more strongly influenced by ductile detailing than by material grade.

There is also a second, more focused body of literature that directly discusses the geometry of the cross section of a column. Chrysanidis and Tegos [24] studied the improvement in the axial and shear capacity that can be obtained when circular RC columns are wrapped in steel jacketing or hybrid jacketing, concluding that the jacketing configuration significantly affects the improvement in the capacity of the RC columns, and that confinement efficiency is one of the main geometry-dependent parameters that determines the amount of improvement that can be made. Kim, Kim and Chang [25] retrofitted rectangular RC columns with 3D textile-reinforced mortar panels and found that the columns exhibited significant improvements in strength, ductility and energy dissipation compared to a rectangular control column. Lee, Han and Kim [26] designed and tested finite-element models of RC columns with polyurea coatings and found that the columns with circular cross sections had better reinforcement effects than the columns with rectangular cross sections for similar amount of coatings, which was explained by the continuous, curvature-free geometry of the circular section. Shi, Choi, Choi and Kang [27] analysed the nonlinear static response of RC frames using SAP2000 and ABAQUS, and found that the column orientation and the storey height have very different performance characteristics and need to be taken into account explicitly in the design and assessment of RC frames.

Specifically for the building scale, Wulandari and Wardi [28] performed pushover analysis on a 3-storey RC building in Padang, Indonesia and showed that the base-shear demand from a new seismic code is approximately 20 per cent higher than that of an existing seismic code for the same building. Anjum et al. [29] investigated a ten storey RC building using pushover and response-spectrum analysis, and found that pushover analysis provides enhanced understanding of potential failure mechanisms compared to response-spectrum analysis alone, making the case for pushover-based comparative studies as this review brings together. The illustrative recent example of this particular comparison is a directly comparative study of a ten-storey RC frame

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

building with six otherwise identical configurations; three with rectangular columns and three with circular columns with comparable cross sectional areas, as discussed in Section 3.1.

2.2 Methods and Technologies Used

Overall, the methods reported in the reviewed studies can be grouped into four categories. The most frequent has been nonlinear static pushover analysis carried out in general-purpose structural software (e.g., ETABS, SAP2000 or DRAIN-2DX), which idealizes the building with lumped plastic hinges at the end of members, applies a monotonically increasing lateral loading pattern, and transforms the capacity curve into seismic demands using the ATC-40 Capacity Spectrum Method, the FEMA-356 Displacement Coefficient Method or the refined FEMA-440 equivalent linearization procedure [4]–[6]. The second is nonlinear (or linear) time-history and incremental dynamic analysis (IDA), which is employed as a guideline for evaluating the accuracy of pushover analysis [14, 18] and as a key tool to quantify collapse risk [20]. The third is the experimental testing of individual members for two dimensional (2D) and/or finite element analysis (FEA) modelling, usually static cyclic testing of isolated members (columns or column-jacket assemblies) to characterise the confinement, ductility and retrofit effectiveness of the circular sections compared to the rectangular sections, directly [9], [24]–[26]. The fourth, which is more recent, is data-driven surrogate modelling, which uses machine-learning algorithms to train on databases of pushover results to predict capacity-curve parameters for new buildings at a fraction of a full nonlinear model's computational cost [30] as discussed in Section 3.2.

The two mathematical relationships come up repeatedly in the literature reviewed and are reproduced here for completeness. The seismic code adopted in India for the design of buildings scales down the base shear to the design value as follows:

$$VB = Ah \bullet W \tag{1}$$

where VB is the design base shear, W is the seismic weight of the building, and Ah is the design horizontal seismic coefficient, which is calculated as follows:

$$Ah = \left(\frac{Z}{2}\right) \bullet \left(\frac{I}{R}\right) \bullet \left(\frac{Sa}{g}\right) \tag{2}$$

It is the zone factor, the importance factor, the response reduction factor, and the spectral acceleration coefficient for the fundamental period and soil type of the building [31]. The alternative displacement coefficient method used by FEMA (FEMA-356) for determining the target displacement is estimated from the elastic period, as detailed in this review the equivalent linearization procedure used by FEMA (FEMA-440) was emphasised in this review.

$$\delta t = C0\, C1\, C2\, C3 \bullet Sa \bullet \left(\frac{Te^2}{4\pi^2}\right) \bullet g \tag{3}$$

The target roof displacement, δt is the effective fundamental period, Te, the spectral acceleration at that period, Sa, and the difference between multidegree-of-freedom and single degree of freedom response, expected inelastic displacement amplification, and cyclic stiffness degradation and dynamic P-delta effects, respectively, are accounted for by the empirical factors, C0 through C3. The ductility demand implied by a given performance point (as used in the FEMA-440 equivalent linearization procedure of Section 3.1) is simply defined as

$$\frac{\mu = \Delta \max}{\Delta y}$$

(4)

This ratio of the max to yield displacement of the equivalent single-degree-of-freedom system is the one that dictates the FEMA-440 procedure at each iteration [6] of the linearized system, which is assigned with the effective (secant) period and equivalent viscous damping.

2.3 Comparative Summary

Table 1 summarizes the studies described in Section 2.1 by their main objective, methodology and main finding to offer a summary reference for evaluating the recent developments described in Section 3 as well as the research gaps described in Section 4.

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

Table 1. Comparative summary of representative studies on nonlinear static assessment and column-shape effects in RC structures.

Ref.	Study focus	Method	Key finding
[11]	Infilled RC frame capacity	Pushover (analytical)	Infill panels reduce global drift capacity from ~2% to 0.3–1%
[12]	Historical RC seismic design	Damage survey / review	Design era correlates strongly with earthquake damage level
[13]	Displacement-based retrofit	Capacity–demand comparison	Displacement targets more suitable than force targets for retrofit
[14]	Pushover load-pattern accuracy	Pushover vs. NLTHA	Accuracy depends on load pattern, ground motion and dynamics
[17]	Algerian-code RC building	Pushover (ETABS/SAP)	Realistic hinge modelling essential for inelastic accuracy
[18]	NSP benchmarking	Pushover vs. recorded response	FEMA-440 CSM more accurate than ATC-40 original CSM
[20]	Infill configuration vs. collapse risk	Incremental dynamic analysis	Fully infilled frames show lowest collapse risk
[22]	Open ground storey	Equivalent lateral force (ETABS)	Open ground storey greatly amplifies ground-storey drift
[23]	Ductile vs. non-ductile detailing	Applied Element Method	Detailing dominates capacity more than material grade
[24]	Circular column jacketing	Experimental (cyclic)	Jacket configuration strongly affects circular-column capacity gain
[25]	Rectangular column retrofit	Experimental (cyclic)	3D textile mortar panels improve strength, ductility, energy dissipation
[26]	Circular vs. rectangular retrofit	Finite-element (validated)	Circular sections show superior polyurea reinforcement effect
[27]	Column orientation / storey level	Pushover (SAP2000/ABAQUS)	Orientation and elevation change performance characteristics
[28]	Code revision effect	Pushover (case study)	Updated code raised base-shear demand by ~20% for same building
[29]	Pushover vs. response spectrum	Pushover + RSA (ETABS)	Pushover reveals failure mechanisms RSA alone cannot capture
[30]	ML surrogate pushover models	Random forest / ANN	$R^2 > 0.8$ achieved at a fraction of full-model computational cost

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

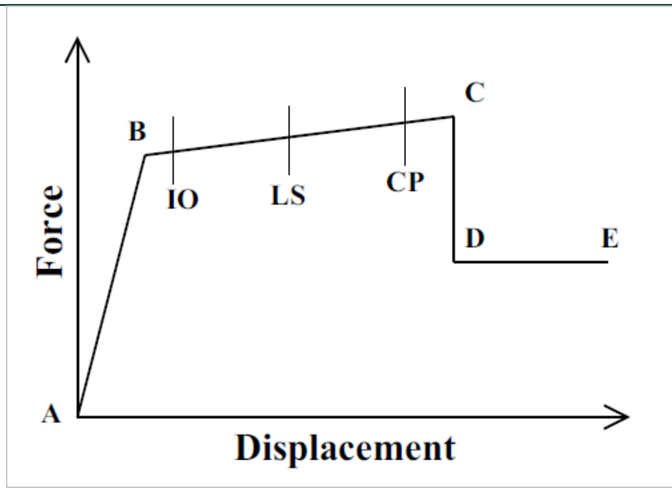

Fig. 1. Generalised force–displacement hinge relationship used in nonlinear static procedures, showing the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) acceptance criteria [5].

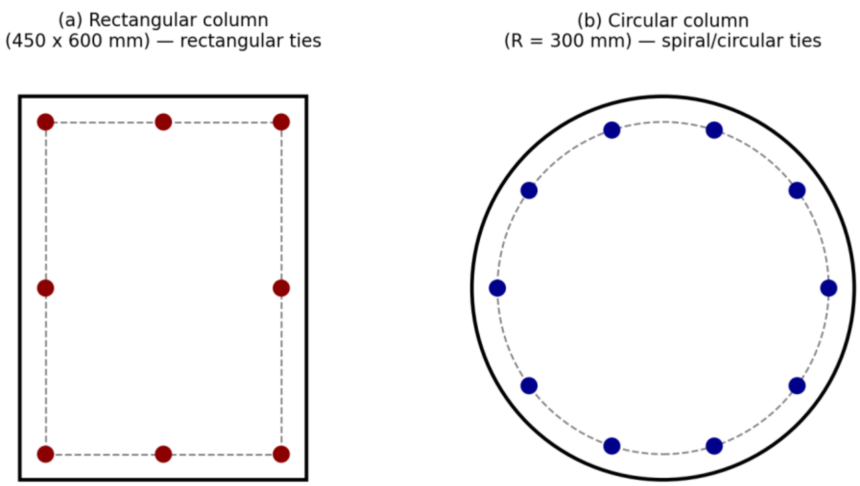

Fig. 2. Schematic cross-sections of (a) a rectangular RC column with rectangular ties and (b) a circular RC column with circular/spiral ties, illustrating the more uniform confinement geometry of the circular section discussed throughout Section 2.1.

3. Current Trends and Developments

3.1 Recent Advancements

Comparative studies of column shape are more common on a building scale since 2020. An illustrative example, recently conducted on a 10 storey (G+9) RC moment resisting frame, applied three cross section dimensions and areas of rectangular columns (450×600 mm, 500×600 mm and 550×600 mm) with three dimensions and areas of the circular columns (250 mm, 300 mm and 350 mm) so that the areas of columns cross sections are approximately equal, while all the rest of the geometric and material parameters are maintained. The storey shear extracted from each level for each of the six configurations is plotted in Fig. 3 and the base storey shear compared directly in Fig. 4. The results demonstrate that the circular configurations are

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

consistently lower in base shear than the rectangular configurations of similar size, especially for the larger size pairings, and slightly lower in storey drift, lower in storey displacement and have a more favourable FEMA-440 performance point at all the size pairings examined, confirming at the building scale the member-level benefit of circular sections established by Chrysanidis and Tegos [24] and by Lee, Han and Kim [26].

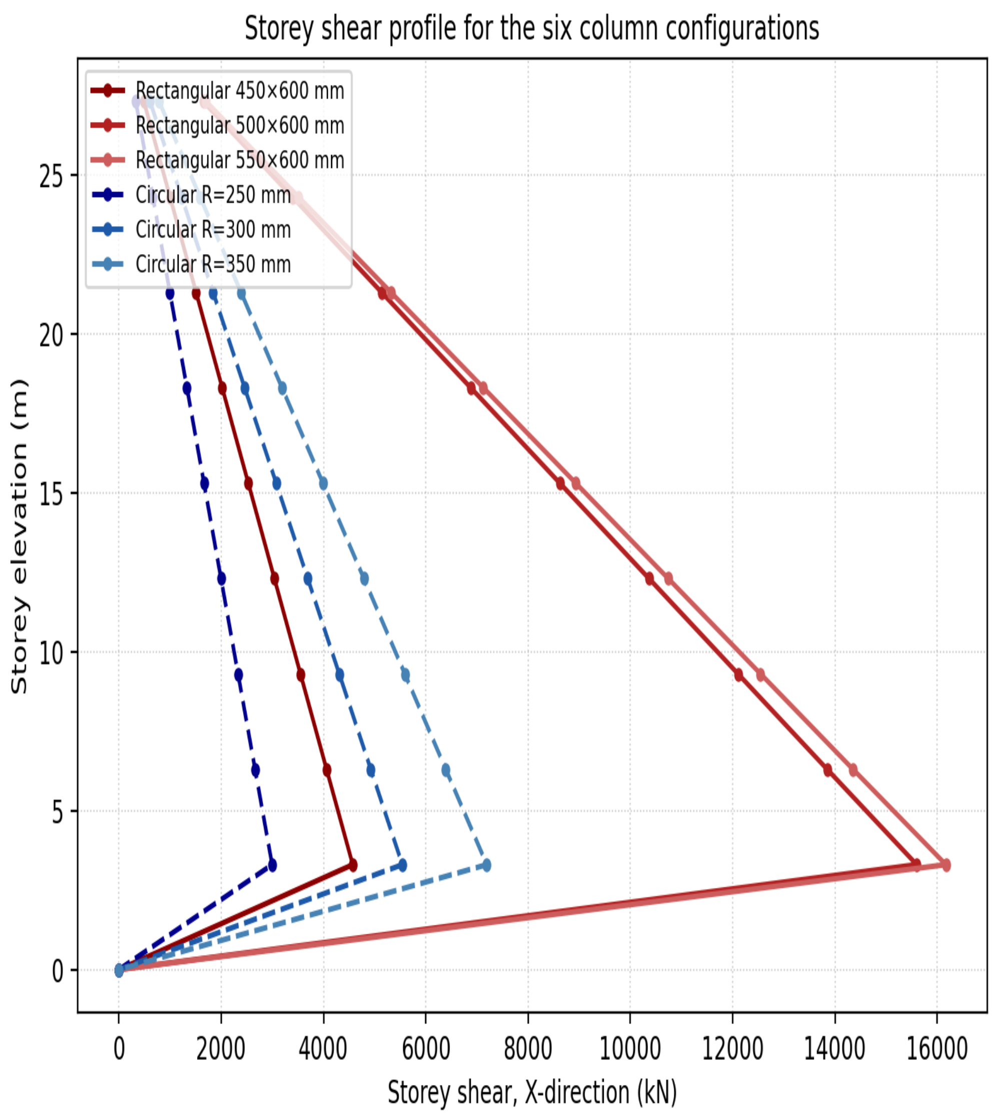

Fig. 3. Storey shear profile (elevation versus storey shear) for six column configurations of a ten-storey RC frame, illustrating the consistently lower shear attraction of the circular column sets relative to rectangular sets of comparable size.

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

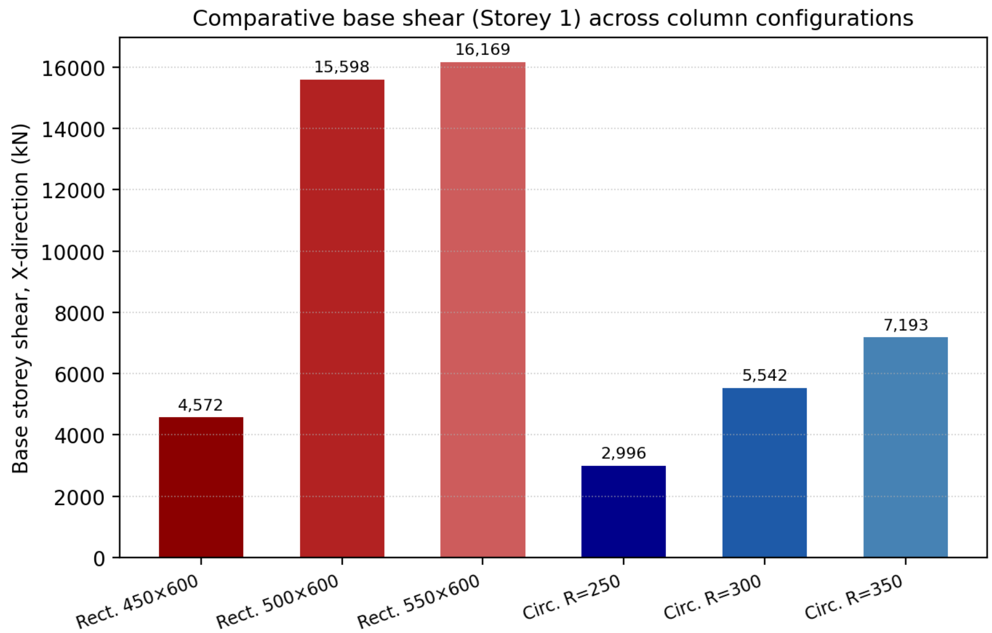

Fig. 4. Comparative base storey shear across the same six column configurations, showing a markedly steeper increase in base shear with cross-sectional size for rectangular columns than for circular columns.

Meanwhile, Anjum et al. [29] compared pushover and response-spectrum analysis on a ten-storey RC building in accordance with the requirements of the 2020 National Building Code of Bangladesh, and found that the two methods complement each other, and pushover analysis is still essential for finding out failure mechanisms which could not be found out by dynamic linear analysis alone. Wulandari and Wardi showed, in a three-storey case study, that a changed national seismic code can have an important effect on the base-shear demand of an otherwise unchanged building, reinforcing the need to continue to validate pushover-based results with the latest seismic hazard maps and code editions.

3.2 Emerging Technologies

Three technology themes are apparent in the recent literature. The first one is data-driven surrogate modelling, where Montes Rodriguez, Angarita Trillos and Arroyo Amell [30] trained random-forest and artificial-neural-network models from a database of low-rise RC frame buildings to directly predict a trilinear approximation to the pushover curve, with a coefficient of determination greater than 0.8 and with a significantly smaller computation time than a nonlinear fibre-based model. These surrogate models suggest the potential for rapid and large-scale seismic screening of building portfolios, even for those with varying columns shapes, without the need to build and analyze a complete, nonlinear model of each building.

The second is advanced retrofit and strengthening technology applicable to or more effective for circular sections: three dimensional textile-reinforced mortar panels [25] and stiff-type and glass-fibre-reinforced polyurea coatings [26], which provide significant improvements in strength, ductility and energy dissipation when compared to unretrofitted sections, particularly the latter where improvements have been reported as being more pronounced on circular sections than rectangular.

The third is an increased tendency to use coupled finite-element and general-purpose structural software (e.g. SAP2000 and ABAQUS) to analyse the effects of column orientation and storey-level effects with a level of local detail that lumped-hinge pushover models (such as ETABS or SAP2000) cannot achieve [27]; this is indicative of a move towards a hybrid analysis

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

workflow approach where the computational efficiency of lumped hinge pushover analysis is coupled with the local accuracy of continuum finite-element modelling at critical sections.

4. Challenges and Limitations

4.1 Technical Issues

Although there are a number of advantages for the adoption of nonlinear static pushover analysis, there are also some technical drawbacks that have been documented. The procedure is based on the assumption that the structural response is generated from the first mode shape and that the response does not change when the structure yields, a condition which becomes less accurate for taller structures and/or structures with high torsion, where the higher mode contributions to storey shear and the storey drift are not negligible [8, 14]. The type of invariant lateral load pattern (uniform, triangular or code-based) significantly influences the resulting capacity curve and hinge-formation sequence, and there is no one best pattern that is consistently found to be superior for the entire range of building height and irregularity that are encountered in practice [14]. In most commercial software, default (auto) hinge properties are derived from average member behaviour reported in the ATC-40 and FEMA-273, and are not necessarily representative of the reinforcement detailing, axial load ratio or most important to this review, the cross-sectional shape of the columns being analysed; while their application to circular columns is generally accepted, they have not been comprehensively validated against experimental data specifically for circular members [6].

4.2 Research Gaps

Based on this review, three areas of research gaps can be identified. First, it is difficult to find studies that isolate the cross-sectional shape of columns as the only independent variable in a complete 3-D, multi-storey building model; the vast majority of the column-shape literature reviewed in Section 2.1 is restricted to examining an isolated member, connection or retrofit assembly [9], [24]–[26] and building-scale comparative studies of this type are not common. Second, pushover-based comparisons often only consider flexural hinge behaviour, rather than accounting for failure modes that are shear critical or joint critical, so the conclusions made about the relative seismic adequacy of circular and rectangular columns cannot be generalised to these failure modes. Third, compared to rectangular columns, current reinforced-concrete and earthquake design codes, such as IS 456 [32] and IS 13920 [33] give much less detailed guidance for the design, detailing and confinement verification of circular columns, even though the performance advantages have been reported in the reviewed literature, there is a gap between the emerging research evidence and current design practice.

5. Future Research Directions

5.1 Potential Improvements

Current nonlinear static procedures could be improved to directly benefit column-shape comparative research. Comparative conclusions would be less sensitive to the choice of invariant load pattern discussed in Section 4.1 [8, 14] if adaptive pushover procedures were used, where the lateral load pattern is updated at each pushover step to reflect the instantaneous mode shape of the structure that becomes increasingly degraded. In the case of circular RC columns, validation of coupled axial-force–biaxial-moment hinge formulations, and their associated interaction surfaces, against experimental data is necessary instead of relying on formulations that have been developed mainly for rectangular columns to improve the validity of pushovers for circular versus rectangular columns specifically. The second research gap identified in Section 4.2 can be resolved by incorporating on the flexural hinges, which are traditionally used, explicit shear-hinge and joint-shear acceptance criteria.

5.2 Opportunities for Future Work

An exciting possibility is to develop a surrogate model specifically for the column-shape comparison problem (as discussed in Section 3.2) – a large database of pushover results could be generated for buildings with different column-shape, size and reinforcement-ratio, and a surrogate model developed to predict the seismic-performance differential between the circular and rectangular column configurations directly from the design parameters, while avoiding the need to run all the nonlinear models illustrated in Section 3.1 as a parametric study. A second opportunity is to validate the pushover-based conclusions presented

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

in this review against nonlinear time-history analysis, using appropriately selected and scaled ground-motion records; if this is possible, and most importantly, with shake-table or full-scale experimental testing of multi-storey subassemblies with circular and rectangular columns, as the vast majority of the evidence presented here is presently based on static, code-based analysis rather than on dynamic or experimental testing. The other three opportunities come from the application of performance-based advantages of circular RC columns documented in Sections 2 and 3 to the development of explicit design and detailing guidance in national seismic codes, with the intention of making the research evidence and design practice that were found to be misaligned in Section 4.2 to get closer.

6. Conclusion

The review has pulled together 30 years of research on the nonlinear static evaluation of RCC structures, with a focus on the comparatively less studied and specific issue of the effect of column cross-sectional shape (circular versus rectangular) on seismic performance. Despite the limitations inherent in its single-mode, invariant-load-pattern idealisation, pushover analysis has proven to be the most common nonlinear static analysis technique for performance-based seismic evaluation, as has been confirmed in the methodological literature, which started with the ATC-40 Capacity Spectrum Method, further developed into the Displacement Coefficient Method developed by FEMA-356, and later with the FEMA-440 equivalent linearization procedure. The literature, which ranges from member-level jacketing to retrofit studies, connection level finite element validation studies and a small, but growing, number of building-level comparative studies all point to the same conclusion: circular RC columns exhibit a consistent seismic performance advantage over rectangular columns of similar cross sectional area, with those advantages being lower base-shear attraction, slightly lower storey drift and displacement, and improved equivalent-linearization performance points.

The three-fold recommendations from this review are of the utmost importance. For further building scale comparative studies, researchers should fix all conditions except column shape as shown in Section 3.1 to eliminate the effects of other factors, such as stiffness, mass, and reinforcement ratio, on the comparative study of column shapes. Secondly, where possible, pushover-based conclusions about column-shape performance should be supported by nonlinear time-history analysis or experimental testing, due to the still limited evidentiary base found in Section 4.2. Third, code-writing bodies may wish to provide further explicit guidance and details for circular RC columns in seismic zones to ensure that the current design practice has been shown to increasingly gain benefits regarding performance, as documented in the research literature reviewed in this article.

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

References

[1] P. Agarwal and M. Shrikhande, *Earthquake Resistant Design of Structures.* New Delhi, India: PHI Learning, 2004.

[2] J. B. Mander, M. J. N. Priestley, and R. Park, "Theoretical stress-strain model for confined concrete," *J. Struct. Eng.,* vol. 114, no. 8, pp. 1804–1826, 1988, doi: 10.1061/(ASCE)0733-9445(1988)114:8(1804).

[3] S. Rocca, N. Galati, and A. Nanni, "Interaction diagram methodology for design of FRP-confined reinforced concrete columns," *Constr. Build. Mater.,* vol. 23, no. 4, pp. 1508–1520, 2009, doi: 10.1016/j.conbuildmat.2008.06.010.

[4] Applied Technology Council, *ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings,* vol. 1. Redwood City, CA, USA: ATC, 1996.

[5] Federal Emergency Management Agency, *FEMA-356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings.* Washington, DC, USA: FEMA, 2000.

[6] Applied Technology Council / Federal Emergency Management Agency, *FEMA-440: Improvement of Nonlinear Static Seismic Analysis Procedures.* Washington, DC, USA: FEMA, 2005.

[7] American Society of Civil Engineers, *ASCE/SEI 41-06: Seismic Rehabilitation of Existing Buildings.* Reston, VA, USA: ASCE, 2007.

[8] K. K. Kuria and O. K. Kegyes-Brassai, "Pushover analysis in seismic engineering: A detailed chronology and review of techniques for structural assessment," *Appl. Sci.,* vol. 14, no. 1, p. 151, 2024, doi: 10.3390/app14010151.

[9] ACI Committee 440, *ACI 440.2R-08: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.* Farmington Hills, MI, USA: American Concrete Institute, 2008.

[10] M. J. N. Priestley, F. Seible, and G. M. Calvi, *Seismic Design and Retrofit of Bridges.* New York, NY, USA: Wiley, 1996.

[11] M. C. Griffith and A. V. Pinto, "Seismic retrofit of RC buildings — A review and case study," Univ. of Adelaide, Australia and European Commission Joint Research Centre, Ispra, Italy, 2000.

[12] S. Otani, "Seismic vulnerability assessment of reinforced concrete buildings," *Faculty Eng. Univ. Tokyo, Ser. B,* vol. 47, pp. 5–28, 2000.

[13] C. Faella, E. Martinelli, and E. Nigro, "Displacement-based assessment and retrofit of existing reinforced concrete framed buildings," *Comput. Struct.,* vol. 80, no. 11, pp. 1001–1009, 2002.

[14] S. Oğuz, "Evaluation of pushover analysis procedures for frame structures," M.S. thesis, Middle East Technical Univ., Ankara, Turkey, 2005.

[15] D. C. Rai, "Seismic evaluation and strengthening of existing buildings," IIT Kanpur and Gujarat State Disaster Management Authority, Gandhinagar, India, 2005.

[16] G. E. Thermou and A. S. Elnashai, "Seismic retrofit schemes for RC structures and local–global consequences," *Prog. Struct. Eng. Mater.,* vol. 8, no. 1, pp. 1–15, 2006.

[17] A. Kadid and A. Boumrkik, "Pushover analysis of reinforced concrete frame structures," *Asian J. Civ. Eng. (Build. Hous.),* vol. 9, no. 1, pp. 75–83, 2008.

[18] R. K. Goel, "Evaluation of current nonlinear static procedures for reinforced concrete buildings," in *Proc. 14th World Conf. Earthq. Eng.,* Beijing, China, 2008.

[19] S. Sarkar, "Design of earthquake-resistant multi-storeyed RCC building on a sloping ground," B.Tech. thesis, Nat. Inst. Technol. Rourkela, India, 2010.

[20] S. Sattar and A. B. Liel, "Seismic performance of reinforced concrete frame structures with and without masonry infill walls," in *Proc. 9th U.S. Nat. / 10th Can. Conf. Earthq. Eng.,* Toronto, Canada, 2010.

[21] B. Monavari, A. Massumi, and A. Kazem, "Estimation of displacement demand in RC frames and comparison with target displacement provided by FEMA-356," in *Proc. 15th World Conf. Earthq. Eng.,* Lisbon, Portugal, 2012.

doi.org/10.5281/zenodo.22224106

ISSN (Online)
3048-8427
Vol. 3 | Issue 3
2026

[22] H. R. Tamboli and U. N. Karadi, "Seismic analysis of RC frame structure with and without masonry infill walls," *Indian J. Nat. Sci.,* vol. 3, no. 14, pp. 1137–1147, 2012.

[23] N. Bodige and P. K. Ramancharla, "Pushover analysis of RC bare frame: Performance comparison between ductile and non-ductile detailing," Int. Inst. Inf. Technol. Hyderabad, Rep. IIIT/TR/2012/-1, 2012.

[24] T. Chrysanidis and I. Tegos, "Axial and transverse strengthening of R/C circular columns: Conventional and new type of steel and hybrid jackets using high-strength mortar," *J. Build. Eng.,* vol. 30, p. 101236, 2020, doi: 10.1016/j.jobe.2020.101236.

[25] S. Kim, S. J. Kim, and C. Chang, "Seismic performance evaluation of RC columns retrofitted by 3D textile reinforced mortars," *Materials,* vol. 15, no. 2, p. 592, 2022, doi: 10.3390/ma15020592.

[26] T.-H. Lee, S.-H. Han, and J.-H. J. Kim, "Numerical evaluation of seismic performance of RC columns strengthened with stiff-type polyurea," *Materials,* vol. 18, no. 8, p. 1839, 2025, doi: 10.3390/ma18081839.

[27] M. Shi, M. Choi, Y. Choi, and S. Kang, "Influences of column orientations and story levels of the RC frames under nonlinear static analysis," *Archit. Res.,* vol. 26, no. 4, pp. 127–138, 2024, doi: 10.5659/AIKAR.2024.26.4.127.

[28] W. Wulandari and S. Wardi, "Seismic performance of an RC building using pushover analysis (case study: Three-storey flat house building in Padang City)," *J. Civ. Eng. Build. Transp.,* vol. 7, no. 1, pp. 18–23, 2023, doi: 10.31289/jcebt.v7i1.8564.

[29] N. Anjum, M. S. Rana, F. Islam, and M. A. Rahman, "Seismic performance evaluation of a 10-story RC building using pushover analysis & response spectrum analysis," *Am. J. Civ. Eng.,* vol. 14, no. 1, pp. 20–38, 2026, doi: 10.11648/j.ajce.20261401.13.

[30] C. D. Montes Rodriguez, C. E. Angarita Trillos, and O. D. Arroyo Amell, "Machine learning–based approach for predicting pushover curves of low-rise reinforced concrete frame buildings," *Structures,* vol. 70, p. 107694, 2024, doi: 10.1016/j.istruc.2024.107694.

[31] Bureau of Indian Standards, *IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures — General Provisions and Buildings,* 5th rev. New Delhi, India: BIS, 2002.

[32] Bureau of Indian Standards, *IS 456: Plain and Reinforced Concrete — Code of Practice,* 4th rev. New Delhi, India: BIS, 2000.

[33] Bureau of Indian Standards, *IS 13920: Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces — Code of Practice,* 2nd rev. New Delhi, India: BIS