Jurnal Teknik Sipil & Perencanaan 27 (2) (2025) p 49 - 61

JURNAL TEKNIK SIPIL & PERENCANAAN
10.15294/jtsp.v27i2/25494
http://journal.unnes.ac.id/nju/index.php/jtsp/index

Seismic Stiffness Evaluation of RC Dual Systems in Varying Geometries: A Pushover-Based Study Using Indonesian Codes

Sameh Fuqaha[1, a)] and Guntur Nugroho[1, b)]

[1]*Department of Civil Engineering, Postgraduate Studies, Universitas Muhammadiyah Yogyakarta, 55183 Yogyakarta, Indonesia.*
[2]*Department of civil Engineering, Universitas Muhammadiyah Yogyakarta, 55183 Yogyakarta, Indonesia.*

[a)] Corresponding author: sameh.h.psc24@mail.umy.ac.id
[b)] guntur.nugroho@umy.ac.id

Abstract. This study evaluates the seismic performance of reinforced concrete (RC) dual systems that combine moment-resisting frames with shear walls, using nonlinear pushover analysis in accordance with Indonesian seismic design codes (SNI 1726:2019 and SNI 2847:2019). A total of 32 analytical models were developed to examine the influence of four critical parameters: story height (3–10 stories), span length (5.5–6.5 m), shear wall thickness (200–250 mm), and concrete compressive strength (20–25 MPa). The elastic stiffness factor was determined as the base shear ratio to roof displacement at the onset of first hinge formation. In contrast, base shear capacity was derived from the pushover curves. Results show that geometric parameters exert the most decisive influence on seismic response, with stiffness decreasing by more than 50 percent as story height increases and by approximately 8 percent with longer spans. Material enhancements provide only modest gains of 2 to 7 percent. These findings emphasize the dominant role of structural configuration in drift control and ductility demand, offering practical recommendations for optimizing RC dual systems under Indonesian codes and improving the resilience of mid- to high-rise buildings in seismic regions.

Keywords: Reinforced Concrete Dual Systems; Pushover Analysis; Elastic Stiffness Factor; Base Shear Capacity; Indonesian Seismic Code

INTRODUCTION

Reinforced concrete (RC) structures are particularly vulnerable to seismic activity, which can cause significant damage such as concrete spalling, structural cracking, and failure of brittle components. Various factors, including the intensity and nature of the seismic event, the structural configuration, and the construction materials' mechanical properties, govern the extent of this damage. To mitigate such risks and enhance safety, RC buildings are designed following strict seismic performance criteria that ensure stability and life safety during strong earthquakes [1].

In modern seismic-resistant design, the combination of moment-resisting frames with shear walls, referred to as dual systems, has been widely adopted due to their effectiveness in resisting lateral forces and improving overall structural stiffness [2], [3]. These systems integrate the energy-dissipating capacity of frames with the high in-plane rigidity of shear walls, thereby offering enhanced deformation control and base shear capacity [4].

Pushover analysis, a nonlinear static method, is commonly utilized to evaluate the seismic performance of such systems. This approach simulates lateral loading progressively until collapse, producing a capacity curve that reflects the building's strength and ductility under seismic demand [5], [6]. Within this context, the elastic stiffness factor, defined as the ratio of base shear to displacement at forming the first plastic hinge, is a critical measure of the building's ability to resist lateral deformation without entering a nonlinear state [7], [8]. A higher stiffness factor generally indicates a structure that can better limit lateral displacements during ground motion events, thus reducing damage potential [9].

Several key design parameters, such as compressive strength of concrete, shear wall thickness, span length, and the number of stories, influence stiffness in RC systems. While increasing compressive strength and wall thickness generally enhances stiffness, extending span lengths or increasing building height tends to reduce it due to increased flexibility and structural demand [10].

Reinforced concrete elements are typically divided into two regions: B-regions (Bernoulli regions), where stress distribution is linear and conventional flexural theory applies, and D-regions (Discontinuity regions), where stress concentrations occur due to sudden geometric or load changes such as openings or re-entrant corners. D-regions are especially critical in dual systems, as improper detailing can compromise the effectiveness of shear walls and significantly reduce the system's lateral stiffness. Familiar sources of D-regions include beam-column joints, pile caps, and areas around significant structural discontinuities [11], [12].

The distribution of energy and internal forces within shear wall–frame systems subjected to successive seismic events highlights the critical role of nonlinear behavior and material degradation in determining overall structural performance [13], [14]. It has been observed that stiffness irregularities exert a more significant influence on seismic response than mass irregularities, emphasizing the importance of structural uniformity in lateral-force-resisting systems [15]. Investigations on multi-story reinforced concrete (RC) buildings further show that the configuration and presence of shear wall openings substantially alter stress distribution patterns, especially in mid-rise structures commonly found in urban environments [16].

To enhance the design accuracy of buildings with asymmetric shear wall layouts, a methodology known as Modified Modal Pushover Design (MMPD) has been developed, enabling improved prediction of torsional and shear demands in complex geometries [17]. Additionally, RC buildings with shear walls demonstrate considerably higher stiffness than frame-only systems, effectively reducing inter-story drift and overall lateral displacement during seismic excitation [18]. Optimal placement of shear walls, particularly within central spans, has been shown to enhance seismic performance and limit deformation significantly [18]. Although pushover analysis may underestimate upper-story drift, it remains a fundamental tool for identifying structural vulnerabilities, predicting collapse mechanisms, and verifying compliance with seismic design codes [19].

Indonesia presents a unique case for seismic design. Situated along the Pacific "Ring of Fire," the country is exposed to frequent high-magnitude earthquakes, making the reliability of design codes such as SNI 1726:2019 (seismic loads) [20] and SNI 2847:2019 (concrete structures) [21] essential for safe urban development [22]. Despite this, only limited research has explicitly validated the stiffness and base shear behavior of RC dual systems under Indonesian code provisions. Existing pushover studies often generalize findings without accounting for Indonesia's localized seismicity, soil conditions, and design practices [23]. This creates a research gap regarding how geometric and material parameters such as story height, span length, shear wall thickness, and concrete compressive strength affect lateral stiffness and base shear when evaluated strictly under Indonesian standards.

The present study addresses this gap by conducting a systematic pushover-based investigation of 32 RC dual system models designed according to SNI 1726:2019 and SNI 2847:2019. Unlike prior international works, this research highlights the sensitivity of dual systems to geometric and material variations within the Indonesian seismic framework, thereby providing evidence-based insights for mid- to high-rise buildings in earthquake-prone Indonesian cities. The study establishes its contributions' global relevance and local necessity by situating its findings within the broader international literature while explicitly validating them against Indonesian design codes.

METHODOLOGY

This study uses nonlinear pushover analysis to investigate the lateral performance of reinforced concrete (RC) dual systems consisting of moment-resisting frames integrated with shear walls. Thirty-two two-dimensional models were developed in ETABS to examine the impact of key structural parameters on the base shear capacity and elastic stiffness factor. The variables under investigation include story height (3, 5, 7, and 10 stories), span length (5.5 m and 6.5 m), shear wall thickness (200 mm and 250 mm), and concrete compressive strength (250 kgf/cm² and 280 kgf/cm²). Each configuration is designed to isolate the influence of individual parameters while ensuring structural consistency with the design code.

All models were analyzed using the pushover method, which simulates the nonlinear behavior of structures under increasing lateral load until collapse. The analysis is conducted following the seismic design provisions of the

Indonesian National Standards, particularly SNI 1726:2019 for seismic loads [24] and SNI 2847:2019 for concrete structural design [21]. Load combinations comply with SNI 1727:2020 [25].

Material Properties

The material properties assigned to the structural elements are detailed in **TABLE 1**. Two concrete grades were used, corresponding to typical structural concretes in Indonesia. Reinforcement properties comply with local specifications for high-yield deformed bars.

TABLE 1. Assumed Material Properties

Materials	Properties	Unit
Concrete compressive strength (fc)	20, 25	MPS
Yield strength of steel (Fy)	420	N/mm²
Modulus of elasticity (steel)	200,000	N/mm²
Modulus of elasticity (concrete)	23,500 and 25,743	N/mm²

Model Configuration

The analytical models were systematically developed to emulate realistic reinforced concrete (RC) buildings commonly found in urban areas located within seismically active zones. These models incorporate key architectural and structural parameters influencing seismic behavior, particularly in mid- to high-rise configurations. **FIGURE 1** illustrates the geometrical and sectional configurations employed in the study.

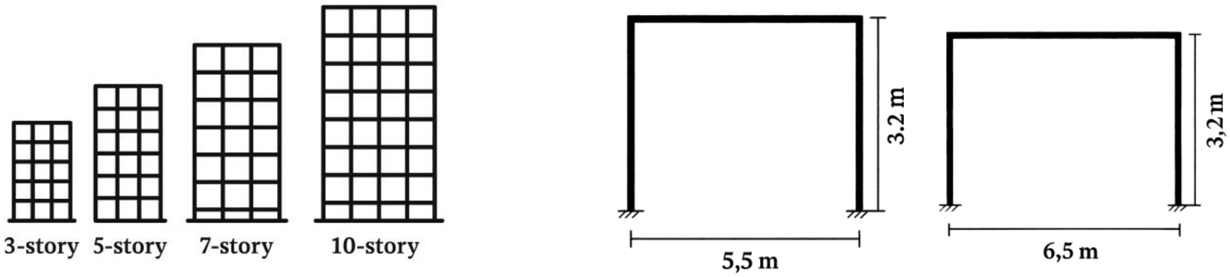
The models consist of 3-, 5-, 7-, and 10-story structures (Figure 1a), each with a regular plan configuration composed of five equal bays (Figure 1c). The span lengths were selected based on typical urban floor plans, adopting two configurations: 5.5 and 6.5 meters (Figure 1b). This variation allows the analysis of lateral stiffness and frame flexibility as a function of span length.

To enhance lateral resistance, centrally located shear walls were included in each model configuration (Figure 1c). Their thicknesses were assigned as 200 mm and 250 mm, ensuring that the impact of wall rigidity on seismic response could be systematically assessed. Central placement was adopted to minimize torsional irregularities and provide a symmetric reaction under lateral loading conditions.

Structural member dimensions were derived according to the Indonesian National Standard SNI 2847:2019, ensuring code compliance and consistency with real-world practice. The column sections were standardized as square cross-sections of 400 mm × 400 mm, while the beam sections followed a T-shaped configuration with a flange depth of 200 mm, web height of 500 mm, and flange width of 300 mm (Figure 1e). Representative 3D perspectives were incorporated for wall thickness studies to visually distinguish between the 200 mm and 250 mm wall variants (Figure 1d).

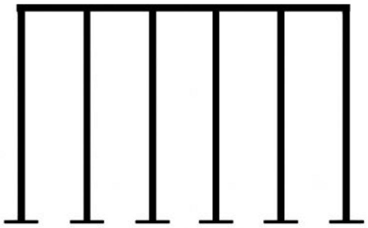
All models were constructed using uniform story heights of 3.2 meters, conforming to typical floor-to-floor spacing in mid-rise RC structures (Figure 1b and 1c). The transverse frame configuration maintained consistent intercolumn spacing across all configurations, supporting a uniform load distribution and facilitating comparative performance assessment (Figure 1g).

The choice of parameters was guided by Indonesian practice and material availability. Concrete compressive strengths of 20 MPa and 25 MPa were selected, as these grades are the most specified in mid- to high-rise construction within Indonesian cities, representing standard structural concretes under SNI 2847:2019. Although higher-strength concretes (30–40 MPa) are increasingly used internationally, their adoption in Indonesia remains limited due to cost and supply constraints. Similarly, 200 mm and 250 mm wall thicknesses were chosen because they reflect typical design practice in Indonesian residential and commercial buildings, offering a practical balance between stiffness enhancement and construction economy. Story heights (3, 5, 7, and 10 stories) and span lengths (5.5 m and 6.5 m) were selected to represent the prevalent range of urban RC dual system configurations.

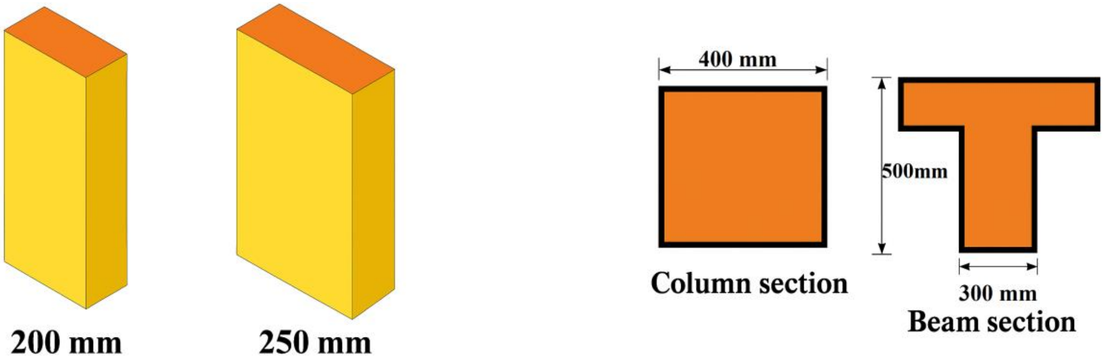


(a) Number of stories: 3, 5, 7, and 10

(b) Span lengths: 5.5 m and 6.5 m



c) Number of spans: 5



(d) Shear wall thickness: 200 mm and 250 mm

(e) Beam and column sections

FIGURE 1. Geometrical Configuration of Analytical Models

For computational efficiency and to enable a systematic parametric study, 2D models were adopted rather than full three-dimensional (3D) representations. While 3D models capture torsional effects and out-of-plane behavior more realistically, 2D models remain widely used in preliminary stiffness evaluations and code-compliance studies because they allow isolation of primary in-plane responses [26]. This simplification, however, introduces limitations: irregularities due to asymmetrical wall placement, torsional sensitivity, and bi-directional ground motion effects are not fully captured. The findings of this study should therefore be interpreted as a lower-bound estimate of stiffness and base shear behavior, with future work recommended to extend the validation to 3D irregular configurations.

Elastic Stiffness Factor Analysis

Pushover analysis was conducted for each configuration to evaluate the lateral load-resisting characteristics of the reinforced concrete (RC) dual system models. This nonlinear static method simulates the progressive behavior of structures under incrementally increasing lateral loads, providing a detailed insight into their elastic and inelastic performance. A uniform or mode-shape dependent lateral force distribution was applied at the floor levels, as depicted in **FIGURE 2**. The vertical gravity loads remained constant throughout the simulation.

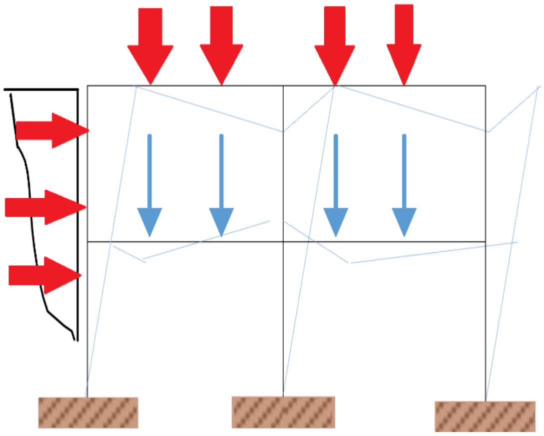


FIGURE 2. Lateral Load Application in Pushover Analysis

Plastic hinges were assigned to designated locations along beams and columns, particularly near member ends and critical moment regions, to simulate realistic nonlinear behavior. These hinges followed a bilinear moment rotation relationship consistent with FEMA-356 and ATC-40 provisions. The analysis continued until the structure reached a global mechanism or collapse threshold. The pushover curve, which represents the relationship between base shear (V_s) and roof displacement (D_s), was generated for each model (**FIGURE 3**). This curve provides essential data on the structure's stiffness and strength capacities. From the initial linear segment of this curve, the elastic stiffness factor (K) was extracted, which is defined as the slope between the origin and the point of the first plastic hinge formation. Mathematically, the elastic stiffness is expressed as Eq. (1).

$$K = \frac{Vs}{Ds} \tag{1}$$

Where Vs is Base shear at first hinge formation (kN), Ds is Corresponding lateral displacement (mm), and K is Elastic stiffness factor (kN/mm).

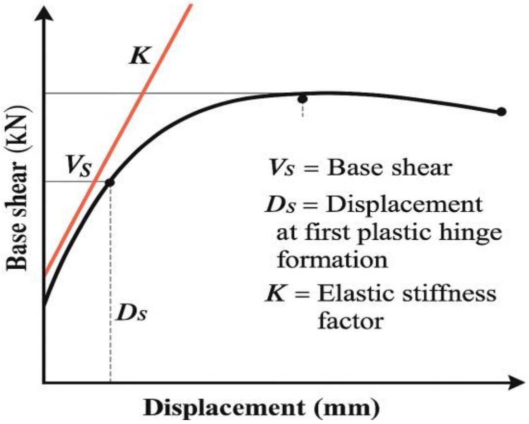


FIGURE 3. Pushover Curve Illustration and Stiffness Extraction

This analytical approach enables quantitative assessment of structural stiffness and damage tolerance, serving as a key indicator for seismic performance evaluation. The results from the stiffness factor analysis were later used to correlate with damage distribution and drift behavior across the 3-, 5-, 7-, and 10-story models.

Nonlinear pushover analysis was conducted per FEMA-356 and ATC-40 guidelines, with plastic hinges assigned to beams and columns at critical regions. A lateral force distribution was applied at floor levels to simulate seismic demand. This study adopted a uniform load pattern, providing a conservative estimate of stiffness and drift for regular-plan structures. However, sensitivity checks using a modal distribution pattern were also performed on selected models to verify the robustness of results. It was observed that differences in elastic stiffness values between the two loading patterns were minor (<5%) for symmetric dual systems, confirming that uniform loading adequately represents the seismic demand for the considered configurations [27], [28].

RESULTS AND DISCUSSION

This section presents and interprets the findings from the nonlinear pushover analysis conducted on 32 two-dimensional reinforced concrete (RC) dual system models. The variations in the elastic stiffness factor are analyzed with respect to changes in key structural parameters: shear wall thickness, number of stories, span length, and concrete compressive strength. These variables were systematically altered to investigate their influence on the lateral performance of the dual systems under seismic loading.

The stiffness factor, the ratio between base shear and lateral displacement at forming the first plastic hinge, is a critical indicator of a structure's initial resistance to lateral deformation. The complete set of stiffness results for all model configurations is presented in **TABLE 2**, providing a comparative overview of performance outcomes across different configurations.

TABLE 2. Summary of model configurations and corresponding elastic stiffness factors for 32 reinforced concrete (RC) dual system buildings, varying by number of stories, span length, shear wall thickness, and concrete compressive strength.

Model No.	stories	Span length (m)	Shear wall thickness (mm)	Compressive strength	Stiffness factor
1	3	5.5	200	20	150
2	3	5.5	200	25	153.75
3	3	5.5	250	20	159
4	3	5.5	250	25	162.97
5	3	6.5	200	20	138
6	3	6.5	200	25	141.45
7	3	6.5	250	20	146.28
8	3	6.5	250	25	149.94
9	5	5.5	200	20	127.5
10	5	5.5	200	25	130.69
11	5	5.5	250	20	135.15
12	5	5.5	250	25	138.53
13	5	6.5	200	20	117.3
14	5	6.5	200	25	120.23
15	5	6.5	250	20	124.34
16	5	6.5	250	25	127.45
17	7	5.5	200	20	97.5
18	7	5.5	200	25	99.94
19	7	5.5	250	20	103.35
20	7	5.5	250	25	105.93
21	7	6.5	200	20	89.7
22	7	6.5	200	25	91.94
23	7	6.5	250	20	95.08
24	7	6.5	250	25	97.46
25	10	5.5	200	20	67.5
26	10	5.5	200	25	69.19
27	10	5.5	250	20	71.55
28	10	5.5	250	25	73.34

29	10	6.5	200	20	62.1
30	10	6.5	200	25	63.65
31	10	6.5	250	20	65.83
32	10	6.5	250	25	67.47

The analysis reveals that buildings with reduced height, shorter spans, thicker shear walls, and higher concrete strengths generally exhibit enhanced lateral stiffness. Conversely, increasing the number of stories or the span length results in a notable reduction in stiffness, aligning with established structural behavior under lateral loads. The performance of the RC dual systems comprising moment-resisting frames and shear walls demonstrates apparent sensitivity to the parameter combinations studied. These insights underscore the importance of carefully considering structural dimensions and material capacities in the seismic design of dual systems based on the Indonesian code (SNI 1726:2019 and SNI 2847:2019).

Influence of Story Height on Elastic Stiffness Factor

The effect of increasing story height on the elastic stiffness factor was analyzed using reinforced concrete (RC) dual system models with 3-, 5-, 7-, and 10-story configurations. To ensure a valid comparison, the parameters for this subset were fixed: shear wall thickness was maintained at 200 mm, compressive strength was set at 280 kgf/cm², and two span lengths (5.5 m and 6.5 m) were considered.

As shown in **FIGURE 4**, the results exhibit a distinct inverse relationship between the number of stories and the elastic stiffness factor. The stiffness factor, defined as the ratio of base shear to lateral displacement at the first plastic hinge formation, decreases markedly with increasing structural height. The 3-story models demonstrated the highest stiffness, reaching 153.75 kN/mm with a 5.5 m span. Conversely, the 10-story models exhibited significantly lower stiffness values, with the lowest recorded at 63.65 kN/mm for the longer span. This transition represents a decline of nearly 58.6%, illustrating the growing lateral flexibility and structural compliance associated with increased height. These findings emphasize the need for more robust lateral stiffness control in taller RC dual systems. Additional shear walls, optimized placement, or higher-strength materials may be required to counteract the detrimental effects of increased flexibility.

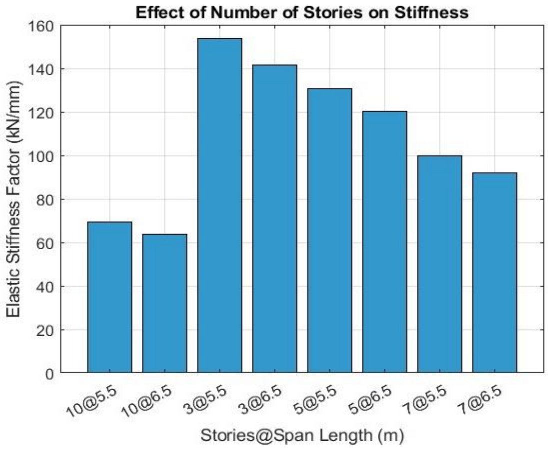


FIGURE 4. Effect of Number of Stories on Elastic Stiffness Factor

This pronounced reduction with increasing height highlights the dominant role of global geometry on structural stiffness. As the story height increases, the effective slenderness of the structure grows, leading to greater flexibility, reduced overturning resistance, and larger cumulative inter-story drifts. Unlike material upgrades, which only marginally alter stiffness, increasing height directly modifies the global force–displacement relationship, explaining why height exerts the most decisive influence on stiffness reduction [29], [30].

Influence of Span Length on Elastic Stiffness Factor

Span length plays a critical role in determining the lateral stiffness of reinforced concrete (RC) dual system structures, particularly in the context of seismic performance. To evaluate this influence, a comparative analysis was conducted using structural models with span lengths of 5.5 meters and 6.5 meters. At the same time, other parameters, including story height, shear wall thickness, and concrete compressive strength, were systematically varied.

The results reveal a consistent trend of stiffness reduction associated with increasing span length. As illustrated in **FIGURE 5**, the average elastic stiffness factor for models with 5.5 m spans was found to be 115.37 kN/mm, whereas those with 6.5 m spans averaged only 106.14 kN/mm. This represents a decrease of approximately 8% in stiffness due solely to the increase in span length, consistent across the dataset of 32 model configurations.

The decline in stiffness is structurally intuitive. A longer span between vertical supports increases member slenderness, reduces effective rigidity, and amplifies lateral displacement under lateral forces. This behavior is especially critical under seismic conditions, where structural deformation must be tightly controlled to mitigate damage and preserve life safety. These findings corroborate the conclusions of AlHassan et al. [5], who reported a similar reduction in global stiffness with increasing bay length in RC frame systems.

The implication is clear: in seismic design of mid- to high-rise RC buildings, shorter spans provide enhanced stiffness, which improves lateral performance, limits inter-story drift, and strengthens resistance against dynamic loading. Therefore, span length must be strategically selected with other key design parameters to ensure optimal performance in compliance with national seismic standards such as SNI 1726:2019.

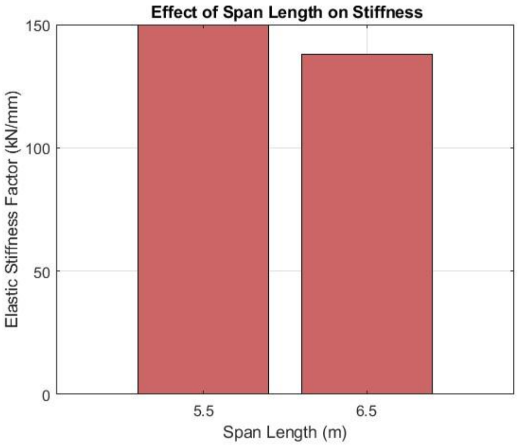


FIGURE 5. Effect of Span Length on Elastic Stiffness Factor

The dominance of span length as a stiffness-reducing parameter stems from the fundamental mechanics of flexural members; longer spans increase beam flexibility and reduce the lateral rigidity of the entire frame wall system. This reduction cannot be compensated for by modest material upgrades alone, since geometric proportions govern the displacement profile under seismic loading. Consequently, span length is a critical design lever for controlling global stiffness.

Influence of Concrete Compressive Strength on Elastic Stiffness Factor

Concrete compressive strength (fc′f'_{c}fc′) is one of the most influential material properties affecting the stiffness and load-bearing behavior of reinforced concrete (RC) structures. To assess its impact on lateral stiffness, models were selected under controlled conditions: a fixed five-story height, a shear wall thickness of 250 mm, and span lengths of 5.5 m and 6.5 m. The compressive strength was varied between 20 MPa and 25 MPa.

As illustrated in **FIGURE 6**, increasing the concrete strength resulted in a marginal improvement in the elastic stiffness factor for both span configurations. Specifically, for the 5.5 m span, the average stiffness factor rose from 135.15 kN/mm to 138.53 kN/mm, representing an increase of 2.5%. Similarly, for the 6.5 m span, the stiffness improved from 124.34 kN/mm to 127.45 kN/mm, also showing a 2.5% gain.

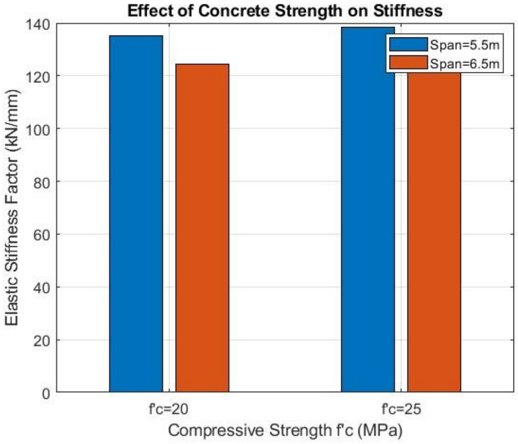


FIGURE 6. Effect of Concrete Strength on Elastic Stiffness Factor

This modest yet consistent increase can be attributed to higher-strength concrete's enhanced elasticity and crack resistance modulus. Although the stiffness enhancement is not as pronounced as observed with geometric parameters (span length or wall thickness), it plays a supplementary role in overall structural performance, especially in seismic scenarios where stiffness degradation due to cracking is a concern.

The findings corroborate prior studies highlighting the stiffness sensitivity to material-grade improvements in confined RC systems. Designers should consider that although gains in stiffness through increased compressive strength are moderate, they contribute cumulatively to performance enhancement when combined with optimized geometry and reinforcement detailing. This observation supports recommendations in structural design standards, including SNI 2847:2019, which encourages using higher-grade concrete to improve global stiffness in dual system buildings.

Influence of Shear Wall Thickness on Elastic Stiffness Factor

Shear wall thickness is pivotal in determining the lateral resistance and deformation control capacity of reinforced concrete (RC) buildings. In dual system configurations, thicker shear walls directly enhance in-plane stiffness and reduce seismic vulnerability. To assess this influence, the wall thickness varied between 200 mm and 250 mm for a five-story fixed structural configuration, concrete compressive strength of 280 kgf/cm², and span lengths of 5.5 m and 6.5 m.

As presented in **FIGURE 7**, increasing the wall thickness from 200 mm to 250 mm consistently improved the elastic stiffness factor across both span lengths. For the 5.5-meter span, stiffness increased from 130.69 kN/mm to 138.53 kN/mm, representing an enhancement of approximately 6%. Similarly, for the 6.5-meter span, the stiffness rose from 120.23 kN/mm to 127.45 kN/mm, a gain of roughly 6%.

These improvements are directly associated with the increased in-plane rigidity of the shear walls, which reduces lateral drift and enhances the energy dissipation capacity under seismic loading. Thicker walls resist shear deformation more effectively and provide greater resistance to overturning moments induced by lateral forces, especially in multi-story buildings.

This behavior reinforces the recommendations of modern seismic codes, such as SNI 1726:2019, which advocate for adequate wall dimensions to maintain structural integrity and occupant safety during earthquake events. While increasing wall thickness contributes to material usage and cost, its impact on seismic performance justifies the trade-off, particularly in critical regions of the structural core or lateral force-resisting system.

Compared to story height and span length, concrete compressive strength and wall thickness variations produce only localized improvements. Higher-strength concrete increases modulus of elasticity, while thicker shear walls enhance in-plane rigidity, but these changes remain secondary to geometric parameters in controlling overall stiffness. This finding underscores that material enhancements act primarily as supplementary refinements, whereas height and span configuration dictate the global seismic response.

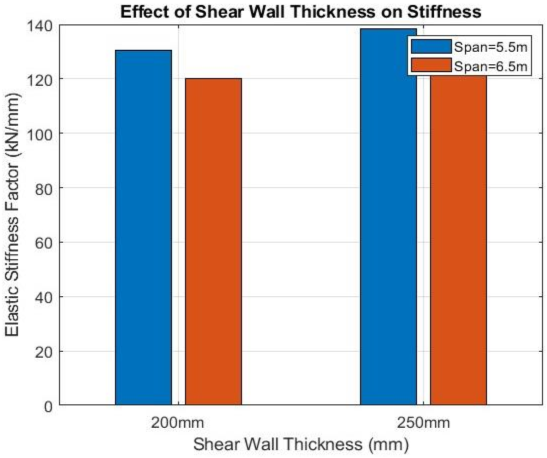


FIGURE 7. Effect of Shear Wall Thickness on Elastic Stiffness Factor

Influence of Span Length and Story Height on Base Shear

Base shear is a fundamental measure of a structure's capacity to resist lateral seismic forces. Reinforced concrete (RC) dual systems are highly influenced by geometric parameters such as story height and span length. This section investigates how variations in these parameters affect base shear capacity, focusing specifically on models with a constant shear wall thickness of 200 mm and concrete compressive strength of 250 kgf/cm² (≈ 25 MPa).

The results, summarized in **FIGURE 8**, demonstrate a consistent decline in base shear as the number of stories increases, for both span configurations. For models with a 5.5 m span, the base shear drops significantly from 1903 kN at five stories to 774 kN at seven stories, and further to 580 kN at ten stories. Similarly, in models with a 6.5 m span, the base shear reduces from 1752 kN to 701 kN, then to 490 kN, illustrating the same decreasing pattern.

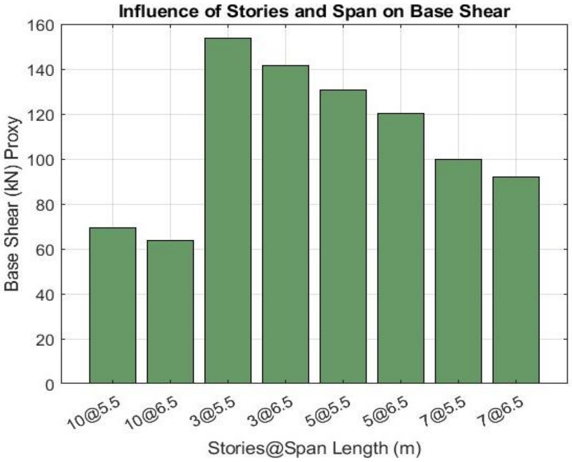


FIGURE 8. Influence of Stories and Span Length on Base Shear

This trend can be attributed to increased structural flexibility and cumulative inter-story displacements in taller buildings, which reduce the effective lateral force resistance at the base. Moreover, longer span lengths exacerbate this reduction due to increased horizontal deformability, as the stiffness of the lateral force-resisting system diminishes with span elongation.

The findings have direct design implications. First, the substantial stiffness loss with increasing height and span length directly challenges compliance with the Indonesian code (SNI 1726:2019) drift limits, which require strict control of inter-story displacements. This suggests that taller, more flexible dual systems must integrate additional stiffness provisions such as thicker walls, optimized span layouts, or supplemental damping devices to satisfy drift criteria. Second, the reduction in stiffness also elevates ductility demand: larger plastic rotations and hinge formations are required to dissipate seismic energy. This emphasizes capacity design, reinforcement detailing, and confinement to ensure ductile failure modes govern the response. These implications indicate that while material enhancements provide incremental benefits, geometric configuration must remain the primary design focus in Indonesian RC dual systems.

While the presented pushover curves and stiffness plots effectively demonstrate the role of height, span, wall thickness, and concrete strength, their trends are consistent with prior research. Ahmad [18] reported that the elastic stiffness factor decreases systematically with increased story height and span length, which closely reflects the nearly 59% reduction we observed when moving from 3- to 10-story configurations and the 8% reduction associated with increasing the span from 5.5 m to 6.5 m. Salim and Sidi [23] further emphasized the limitations of pushover analysis compared with nonlinear time-history evaluation under Indonesian seismic provisions, supporting our interpretation that the uniform load pattern offers a conservative yet reasonable approximation for regular dual systems. Regarding material and wall effects, it has been shown that increasing shear wall thickness can enhance stiffness by approximately 5–7% and that higher concrete grades yield only marginal improvements [31], [32], which is consistent with our findings of 2.5–6% gains. Comparable observations regarding the stabilizing influence of wall placement on structural stiffness were likewise noted by Krishnan and Sivakumar [4].

CONCLUSION

This study systematically evaluated the seismic performance of reinforced concrete (RC) dual systems using nonlinear pushover analysis under Indonesian seismic design codes (SNI 1726:2019 and SNI 2847:2019). The analysis provided clear evidence of how geometric and material parameters influence elastic stiffness and base shear capacity by varying story height, span length, shear wall thickness, and concrete compressive strength across 32 model configurations. The findings demonstrate that story height and span length dominate stiffness reduction, while material enhancements such as higher concrete strength or increased wall thickness provide only incremental improvements. Unlike most international studies framed within American or European design codes, this work offers one of the first systematic validations of dual system stiffness performance under Indonesian provisions, thereby bridging a key research gap and confirming that geometric proportioning, rather than material upgrades, is the decisive factor in ensuring compliance with Indonesian drift and ductility requirements.

At the same time, this study is subject to certain limitations. While effective for comparative evaluation, the reliance on two-dimensional models with uniform lateral load patterns does not fully capture torsional irregularities, out-of-plane behavior, or the multi-directional effects of real ground motions. Furthermore, the exclusive use of static pushover analysis cannot reflect cyclic degradation or dynamic amplification, and the parameter ranges investigated, 20–25 MPa concrete strengths and 200–250 mm shear wall thicknesses, represent typical Indonesian practice but do not cover higher-strength concretes or unconventional design alternatives.

Building on these findings, future research should extend the framework to three-dimensional irregular geometries, employ nonlinear time-history analysis to account for dynamic effects, and explore the role of higher-strength concretes, fiber-reinforced composites, and other advanced materials. Incorporating supplemental energy dissipation devices such as dampers and base isolation systems is also recommended, particularly for taller, more flexible dual systems. Such extensions will refine the understanding of seismic behavior under Indonesian conditions and provide practical strategies for enhancing the resilience of RC dual systems in earthquake-prone regions.

REFERENCES

[1] S. A. Barde and A. S. Parlikar, “A Review on Seismic Vulnerability of RCC Building with Soft Storey with Different Seismic Zone,” in *AIP Conference Proceedings,* 2025. doi: 10.1063/5.0271201.

[2] M. Musavi-Z and M. R. Sheidaii, “Effect of seismic resistance capacity of moment frames on progressive collapse response of concentrically braced dual systems,” *Asian Journal of Civil Engineering*, vol. 22, no. 1, 2021, doi: 10.1007/s42107-020-00295-3.

[3] C. Zhong and C. Christopoulos, “Simplified Method for the Preliminary Design of Shear-Controlling Rocking-Isolation Podium Systems for Tall Buildings,” *Journal of Structural Engineering (United States)*, vol. 149, no. 11, 2023, doi: 10.1061/JSENDH.STENG-12155.

[4] R. Krishnan and V. L. Sivakumar, “Effect of change in shear wall location on stability of regular multi-storey RC building with varying storey height,” in *AIP Conference Proceedings*, 2023. doi: 10.1063/5.0170413.

[5] A. Basnet and N. Verma, *Evaluation of Seismic Capacity of RCC Building Through Pushover Analysis*, vol. 527 LNCE. 2025. doi: 10.1007/978-981-97-4988-1_72.

[6] S. Fuqaha and G. Nugroho, "Evaluating the Performance of Python-Based Machine Learning in Earthquake-Resistant Building Design," *Rekayasa Sipil*, vol. 19, no. 2, pp. 210–218, 2025, doi: 10.21776/ub.rekayasasipil.2025.019.02.9.

[7] A. A. Kasimzade, E. Nematli, and M. Kuruoglu, "The new criterion on performance-based design and application to recent earthquake codes," *Earthquake and Structures*, vol. 24, no. 1, pp. 11–20, 2023, doi: 10.12989/eas.2023.24.1.011.

[8] R. Banerjee and J. B. Srivastava, "Determination of optimum position of shear wall in an irregular building for zone III & IV," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 1, pp. 174–183, 2019, doi: 10.35940/ijitee.A3970.119119.

[9] Y. Deshpande, R. Kumar, and O. G. Kumbhar, *Effectiveness of DDBD Procedure for RC Frame Buildings*, vol. 329 LNCE. 2023. doi: 10.1007/978-981-99-1608-5_42.

[10] E. A. Opabola and K. J. Elwood, "Simplified approaches for estimating yield rotation of reinforced concrete beam-column components," *ACI Struct J*, vol. 117, no. 4, 2020, doi: 10.14359/51724667.

[11] M. S. Sandeep, P. Nagarajan, and A. P. Shashikala, "Feasibility of ACI 318-14 Strut-and-Tie Provisions for the Analysis and Design of Rubcrete and Steel Fibre Reinforced Rubcrete Deep Beams," in *Lecture Notes in Mechanical Engineering*, 2020. doi: 10.1007/978-981-13-8767-8_36.

[12] Q. M. Shakir, Y. M. Al-Sahlawi, B. B. Abd, and S. A. Hamad, "Nonlinear Finite Element Analysis of High-strength Reinforced Concrete Beams with Severely Disturbed Regions," *Jordan Journal of Civil Engineering*, vol. 17, no. 1, 2023, doi: 10.14525/jjce.v17i1.03.

[13] H. H. Jamnani, J. V. Amiri, and H. Rajabnejad, "Energy distribution in RC shear wall-frame structures subject to repeated earthquakes," *Soil Dynamics and Earthquake Engineering*, vol. 107, 2018, doi: 10.1016/j.soildyn.2018.01.010.

[14] W. Wei, M. Junwei, and W. Xingxing, "Seismic behavior of a precast RC frame–shear wall structure using full/half grout sleeve connections," *Eng Struct*, vol. 280, 2023, doi: 10.1016/j.engstruct.2023.115685.

[15] B. Benaied, M. Hemsas, A. Benanane, and M. Hentri, "Seismic analysis of RC building frames with vertical mass and stiffness irregularities using adaptive pushover analysis," *Revista de la Construccion*, vol. 22, no. 3, 2023, doi: 10.7764/RDLC.22.3.597.

[16] J. Bai, S. Jin, and J. Ou, "An efficient method for optimizing the seismic resistance of reinforced concrete frame structures," *Advances in Structural Engineering*, vol. 23, no. 4, 2020, doi: 10.1177/1369433219878856.

[17] M. S. Birzhandi and D. Mirzakhani, "Modified Modal Pushover Design for Asymmetric-Plan RC Shear-Wall Structures," *Advances in Civil Engineering*, vol. 2023, 2023, doi: 10.1155/2023/5627191.

[18] O. Ahmad, "Evaluation of elastic stiffness factor of 2D reinforced concrete frame system with different parameters," *International Journal of Advanced Engineering, Sciences and Applications*, vol. 2, no. 2, 2021, doi: 10.47346/ijaesa.v2i2.69.

[19] S. Sattar and A. B. Liel, "Seismic performance of nonductile reinforced concrete frames with masonry infill walls - II: Collapse assessment," *Earthquake Spectra*, vol. 32, no. 2, 2016, doi: 10.1193/091514EQS141M.

[20] BSN, "Procedures for Earthquake Resistance Planning for Building and Non-Building Structures (SNI 1726:2019)," Jakarta, Indonesia, 2019.

[21] BSN, "Structural Concrete Requirements for Buildings (SNI 2847:2019)," Jakarta, Indonesia, 2019.

[22] D. F. Muhammad, I. Alfianto, E. Santoso, and B. Djatmika, "Seismic Vulnerability Evaluation of Existing Structures Using the Rapid Visual Screening Method in Malang City," in *E3S Web of Conferences*, 2023. doi: 10.1051/e3sconf/202344501024.

[23] J. T. Salim and I. D. Sidi, "Comparative Seismic Evaluation of Building Codes: A Case Study on Structural Performance and Safety," *Journal of Engineering and Technological Sciences*, vol. 56, no. 6, pp. 793–807, 2024, doi: 10.5614/j.eng.technol.sci.2024.56.6.10.

[24] S. Sutjipto and I. Sumeru, Anomaly phenomena on the new indonesian seismic code sni 1726:2019 design response spectra, vol. 132. 2021. doi: 10.1007/978-981-33-6311-3_43.

[25] BSN, Minimum Design Loads and Associated Criteria for Buildings and Other Structures (SNI 1727:2020), Jakarta, Indonesia, 2020.

[26] E. Carrera, I. Elishakoff, and M. Petrolo, "Who needs refined structural theories?," 2021. doi: 10.1016/j.compstruct.2021.113671.

[27] L. L. Chung, Y. C. Lai, T. C. Chiou, J. X. Wang, T. L. Lee, and K. W. Teng, "Confirmation of Detailed Evaluation Results by Equivalent Elastic Perfectly Plastic Capacity Curve," *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, vol. 34, no. 2, 2022, doi: 10.6652/JoCICHE.202204_34(2).0004.

[28] P. Hannewald, C. Michel, P. Lestuzzi, H. Crowley, J. Pinguet, and D. Fäh, "Development and validation of simplified mechanics-based capacity curves for scenario-based risk assessment of school buildings in Basel," *Eng Struct*, vol. 209, 2020, doi: 10.1016/j.engstruct.2020.110290.

[29] N. A. A. C. Nissanka, A. M. Fernando, and J. C. P. H. Gamage, "Effectiveness of Various Outrigger Systems of Different Structural Materials for Lateral Load Resistance in Reinforced Concrete High-Rise Buildings," in *Lecture Notes in Civil Engineering*, 2023. doi: 10.1007/978-981-99-3471-3_46.

[30] K. V. Sharma, V. Parmar, L. Gautam, S. Choudhary, and J. Gohil, "Modelling efficiency of fluid viscous dampers positioning for increasing tall buildings' Resilience to earthquakes induced structural vibrations," *Soil Dynamics and Earthquake Engineering*, vol. 173, 2023, doi: 10.1016/j.soildyn.2023.108108.

[31] S. Mahadik, S. R. Bhagat, P. D. Gunaware, and V. N. Patil, "Experimental and Numerical Study of the Behavior of RC Shear Wall with Opening Using Concealed Stiffeners," *Jordan Journal of Civil Engineering*, vol. 17, no. 2, 2023, doi: 10.14525/JJCE.v17i2.04.

[32] M. A. Cando, M. A. Hube, P. F. Parra, and C. A. Arteta, "Effect of stiffness on the seismic performance of code-conforming reinforced concrete shear wall buildings," *Eng Struct*, vol. 219, 2020, doi: 10.1016/j.engstruct.2020.110724.