https://doi.org/10.31436/iiumej.v26i1.3321

FACTORS INFLUENCING THE ELASTIC STIFFNESS FACTOR IN REINFORCED CONCRETE STRUCTURE OF DUAL SYSTEM USING PUSHOVER ANALYSIS

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(Received: 10 June 2024; Accepted: 20 November 2024; Published online: 10 January 2025)

ABSTRACT: Stiffness is one of the most critical characteristics of a building, which is considered for public safety against earthquake loads and refers to displacement resistance. Buildings must be built with proper strength and stiffness. This study uses pushover analysis to evaluate the parameters influencing the stiffness of the RC Dual system. The research used ASCE 7-10 and ACI 318-08 codes to design 24 two-dimensional buildings. Pushover analysis is conducted in the models using the ETABS software. Factors, including the number of stories, span length, thickness of the shear walls, and compressive strength, were considered while evaluating the stiffness and base shear of the designed buildings. The highest stiffness factor is (149.30) found in low-rise buildings with smaller span lengths, higher shear wall thickness, and higher compressive strength. In comparison, the lowest stiffness factor of (27.88) appeared in high-rise buildings with longer span lengths, lower shear wall thickness, and lower compressive strength. This study analyzed a dual system consisting of a moment-resisting frame and a shear wall. In further studies, other structural systems can be considered. By increasing the span length from 5.5m to 6.5m, the stiffness factor decreases by 8%. While by increasing shear wall thickness, the stiffness factor increased by 4.5%. Since every sample consists of two-dimensional dual systems, the influence of torsion is avoided. Future work should take torsional impacts into account since they have the potential to impact the design.

ABSTRAK: Untuk menyediakan keselamatan umum terhadap daya gempa, salah satu ciri bangunan yang paling penting ialah kekakuan, yang menerangkan tentangan terhadap anjakan. Bangunan mesti dibina dengan kekuatan dan kekakuan yang betul. Kajian ini menggunakan analisis pushover untuk menilai parameter yang mempengaruhi kekukuhan sistem RC Dual. Penyelidikan menggunakan kod ASCE 7-10 dan ACI 318-08 untuk mereka bentuk 24 bangunan dua dimensi. Analisis pushover dijalankan dalam model menggunakan perisian ETABS. Beberapa faktor, termasuk bilangan tingkat, panjang rentang, ketebalan dinding ricih, dan kekuatan mampatan, diambil kira semasa menilai kekukuhan dan ricih asas bangunan yang direka bentuk. Faktor kekukuhan tertinggi yang diukur dengan membahagikan ricih asas kepada anjakan (149.30) muncul di bangunan bertingkat rendah dengan panjang rentang yang lebih kecil, ketebalan dinding ricih yang lebih tinggi, dan kekuatan mampatan yang lebih tinggi. Manakala faktor kekakuan terendah (27.88) terdapat pada bangunan bertingkat tinggi dengan panjang rentang yang lebih panjang, ketebalan dinding ricih yang lebih rendah, dan kekuatan mampatan yang lebih rendah. Hanya kerangka tahan momen dengan dinding ricih yang dipanggil model (sistem dwi) telah dianalisis dalam kajian ini; sistem struktur lain boleh dipertimbangkan dalam kajian lanjut. Dengan meningkatkan panjang rentang daripada 5.5m kepada 6.5m, faktor kekakuan berkurangan sebanyak 8%. Manakala dengan meningkatkan ketebalan dinding ricih, faktor kekakuan meningkat sebanyak 4.5%. Memandangkan setiap sampel terdiri daripada sistem dwi dua dimensi, pengaruh kilasan dielakkan, kerja masa hadapan harus mengambil kira kesan kilasan kerana ia berpotensi memberi kesan kepada reka bentuk.

***KEYWORDS**: reinforced concrete structure, pushover analysis, dual system, base shear, elastic stiffness factor*

1. INTRODUCTION

In reinforced concrete structures, earthquakes can result in various damages like concrete bursting, cracking, and failure of nonductile parts. The degree of damage is determined by several factors, including the type of seismic event, building design, and construction materials. Structures are designed to withstand earthquakes and built according to specific criteria to improve human life stability during severe seismic events [1, 2]. A moment-resistant frame combined with a shear wall makes the structure stiff and capable of withstanding lateral loads [3]. Dual systems, such as structural reinforced concrete (RC) with shear walls, were widely employed as structural resistance against attraction and lateral forces [4]. The pushover analysis method determines the maximum load a structure can withstand, indicating its capability to endure earthquakes [5].

In pushover analysis (nonlinear static method), a push is applied to the top level of the structure until it collapses. The collapse of the structure is represented by the relationship between maximum load and displacement in the ETABS pushover analysis [6]. Static inelastic analysis determines the strength requirement and displacement of the structure during the seismic period. The main objective of pushover analysis is to assess the desired quality level of the structure [7]. The objective of the elastic stiffness factor of a building is the ability to resist loads applied to the structure without causing plastic hinges, and it can be used to determine the building's natural period. The pushover curve can be used to determine this component by dividing the base shear by the lateral displacement at the first appearance of the plastic hinge [8]. Stiffness is the capacity of a beam or column to resist deformation when load is applied. One purpose of building design is to ensure that no part of the structure is exposed to damage or cracking that may cause its collapse after construction [9]. The capability curves, also known as pushover curves, are base shear load-deformation curves that point in the direction of the lateral deformation of the building and show the nonlinear characteristic of the structure. The pushover curve provides an expression of structural capabilities. The most effective way to map the load-deformation curves was to follow the base shear by considering both roof displacement and the base shear [10]. It is known that stiffness increases with increases in compressive strength and shear wall thickness. Conversely, extending the span length or adding stories from low to high causes the stiffness factor to decrease.

Each reinforced concrete element is classified into two types: B-regions (Bernoulli regions), which have a uniform distribution of stresses and no substantial turbulence in stress line contours. The flexural analytical concept can be employed in this region. The second type of region is the D-region (Discontinuity region), which occurs when there is a discontinuity in the distribution of stresses or when contour lines are disturbed [11]. The D-region (disturbed region) in reinforced concrete (RC) constructions refers to locations around discontinuities, like openings, heavy loads, or abrupt shifts in geometry, where stress distribution differs from a standard beam or column behavior. The D-region gets non-uniform stress distributions. It may become a weak point if it is not properly reinforced or accurately calculated, reducing the elastic stiffness factor. The stiffness of the dual system depends on the D-region's integrity, which requires material qualities and stress transfer mechanisms. D-regions can be caused by changes in geometry, like pile caps, openings, beam-column joints, and non-prismatic beams.

Due to the significant stresses in the D-regions, the cross-section of the members will not remain plane after deflection [12].

Jamnani et al. [13] evaluated the energy distribution in reinforced concrete shear walls and structural frames when subjected to multiple earthquakes by determining the stability of the structures. The paper investigated the nonlinear action and strength distribution of RC shear wall composite frames. Reliable predictions can be made when comparing the impacts of several earthquakes on structures using a single wave analysis. Generally, repetitive building earthquakes lead to fading inelastic strength. Benaied et al. [14] investigated the reaction of inelastic reinforced concrete structures with mass and stiffness irregularities to seismic activity. By incorporating vertical irregularities into various designs of a ten-story building, the responses of key parameters are analyzed and quantified. Stiffness irregularities were shown to have a more significant influence than mass irregularities on the seismic response, which were discovered to have a negligible effect on the building's seismic behavior. The outcome demonstrates that irregular structures must be built to reduce seismic effects and cannot satisfy seismic design standards.

Bertagnoli et al. [15] present a software study of the reinforced concrete structure. The structure under explanation is a combination of beams and columns that provides part of the structural building frame of ten-story RC structures. It is also subjected to lateral forces and a progressively increasing longitudinal displacement of the central column to simulate the column removal scenario. In urban areas of India, mid-rise residence reinforced concrete buildings with several stories that range from 8 to 10 or 12 will become ordinary. Shear walls were provided in mid-rise reinforced concrete frames for lateral force tolerances. Considering the shear walls were also provided via openings, in addition to the drifting floor stiffness, moment, and shear, it is essential to look into how these openings impact the stresses in the shear walls. A three-dimensional analysis was conducted to design the shear wall across the building structure. This study emphasizes the significance of the locations and sizes of each of those openings [16].

Birzhandi et al. [17] present a new approach to the design of one-way asymmetrical plan reinforced concrete wall structures. The modified modal pushover design method (MMPD) is the name given to this approach. Three eight-story structures have been planned accordingly to evaluate the impact of two distinct reinforcement area distributions on the NRHA requirements for each level. The elastic jagged response spectrum has higher mode contributions in responses of all structures. The mean-matched smoothed displacement response spectrum standard deviation curve is also applied to evaluate the shear and torsional stresses indicated by these two response spectra for stories. In conclusion, MMPD offers a safe design for the flexural capacity of shear walls on both the stiff and flexible sides of the plan. This highly reliable and cost-effective approach uses the structure's responses over time to adapt and optimize the design for future needs. The outcomes demonstrate how accurately the MMPD approach calculates the stiffness and strength of shear walls that resist earthquakes. Ahmad [18] used twelve two-dimensional reinforced concrete frames with various span lengths, and the number of stories, with shear walls and without shear walls, were subjected to pushover analysis to determine the impact of these factors on the elastic stiffness factor. The study's findings demonstrated that the stiffness factor reduces as the number of stories increases, and the elastic stiffness factor increases when the span length increases. Frames with shear walls are much stiffer compared to frames without shear walls. Using a shear wall in a building will effectively reduce the displacement of the structure and story drift. It would reduce the damage caused by lateral forces like earthquakes. Depending on the study, the highest performance that reduces displacement and story drift is achieved by evenly placing the shear wall of the structures in the middle span of the building [19].

The suitability of pushover analysis for the seismic assessment of mid-rise and high-rise buildings is examined. Pushover analysis overestimates the highest displacements and underestimates story drifts, especially those occurring on the tallest floors of structural buildings. The shear wall's optimal location for a multiple-story structural building has been investigated. Nonlinear structural analysis is performed for various shear wall locations inside building structures. An eight-story building structure was given. A pushover curve was compared with several models by using the ETABS program. The results show that having a shear wall at a suitable location is more critical when base shear and displacement are present in building structures [20].

Elements that affect long-term stiffness, including creep, shrinkage, and concrete, should be considered. The advantages of the pushover method include handling nonlinear behavior, simulating progressive collapse, supporting performance-based design, identifying weaknesses in structure, developing hinge properties, and ensuring code compliance. Exploring how the height and slenderness of a building affect its elastic stiffness, particularly in very tall buildings, is an essential area of study. This research can lead to new insights into designing super-tall structures that remain stable and resilient under lateral loads. Further investigation is necessary about the influence of new materials (such as fiber-reinforced polymers and high-performance concrete) on the stiffness factor of dual systems.

2. METHODOLOGY

The study studied reinforced concrete dual systems (moment-resisting frame with shear wall) to determine the base shear and elastic stiffness factors. Twenty-four two-dimensional models with different shear wall thicknesses, story numbers, span lengths, and compressive strengths were designed to identify stiffness. Various models have been used by adapting each parameter to each other, and each model contributes to identifying and evaluating the effect of these variables. ASCE 7-10 and ACI 318-08 codes have been used in this investigation. Pushover analysis is applied to the models using the ETABS computer program.

2.1. Assumed Material Properties

Materials that were used in this article are shown in Table 1.

Table 1. Material Properties

Materials	Properties
Compressive strength ($f'c$)	250 kgf/cm^2 and 280 kgf/cm^2
Fy of reinforcement steel	420 N/mm^2
Modulus of elasticity of steel	200,000 N/mm^2
Concrete modulus of elasticity	23500 and 25743 N/mm^2

* Fy: Yield Strength

*ACI: American Concrete Institute

*ASCE: American Society for Civil Engineering

2.2. Description of Models

Details of the models that were used are shown in Figure 1.

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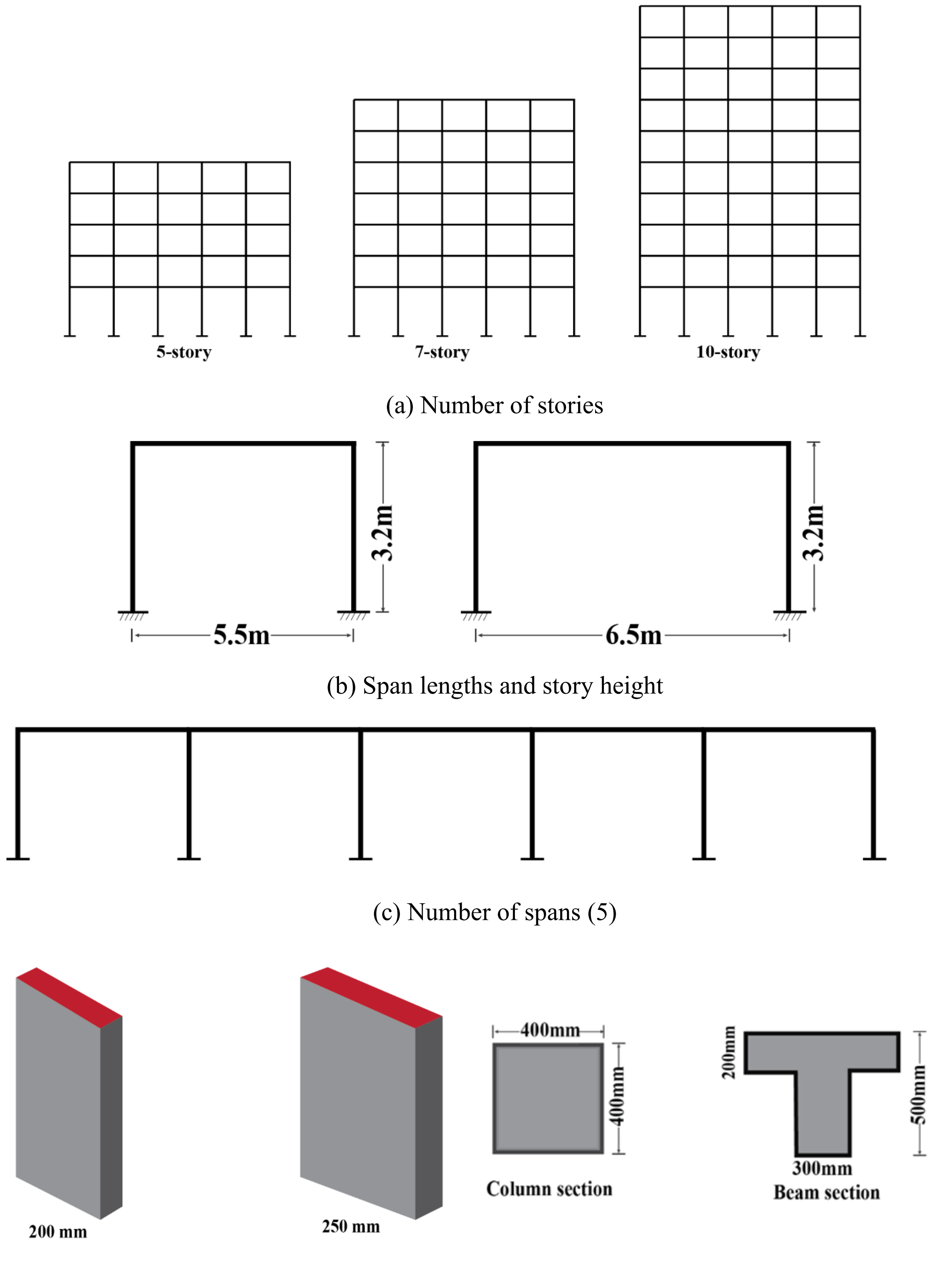

(a) Number of stories

(b) Span lengths and story height

(c) Number of spans (5)

(d) Shear wall thickness

(e) Column and beam section sizes

Figure 1. Details of the models.

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2.3. Elastic Stiffness Factor Analysis

Pushover analysis is a valuable technique for analyzing the behavior of the building, recording yielding and cracking when the base shear rate increases. Static analysis displays the degree of performance, the collapse mechanism, and the behavior of elements in the structure [21]. Static analysis shows the relationship between base shear and displacement. Figure 2 shows the building when the lateral load adds a push.

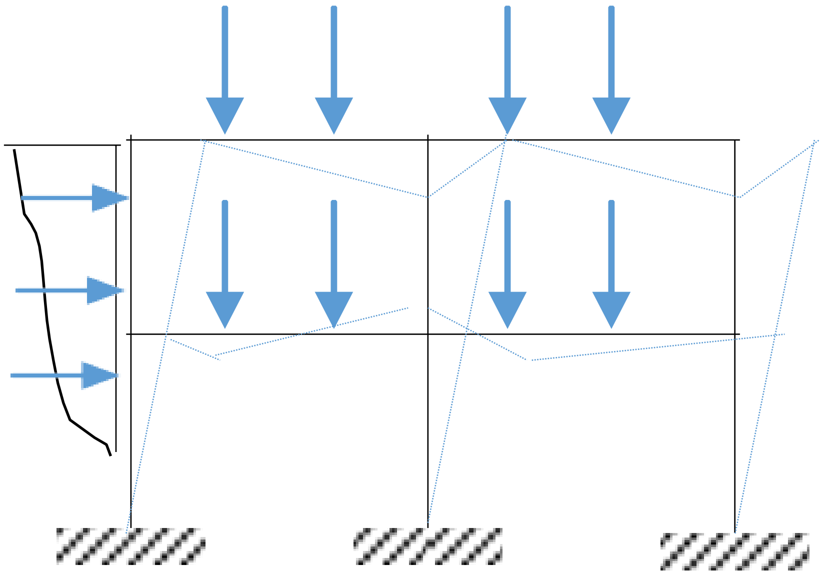

Figure 2. Pushover illustration [22]

The two-dimensional mathematical models of the dual systems are first built and designed, with hinges given to the frames. Pushover analysis is then stated, and the load patterns of pushover analysis have been assigned to a direction. All the models are pushed up to rupturing displacement at the dictated joint. This research looks at the acceleration pattern of lateral load, which draws a pushover curve up to the point where the structure collapses. In this acceleration pattern, the lateral load is increased until the structure reaches the system's maximum capacity. Following pushover analysis, a curve shows the structure's lateral displacement and base shear. An example of the elastic stiffness factor calculation process via a pushover curve can be observed in the sample below.

The stiffness factor is found by dividing the base shear by the lateral displacement at the occurrence of the first plastic hinge. After constructing the pushover curve, the base shear is taken from the curve, and the elastic stiffness factor is determined [23]. Figure 3 illustrates extracting the highest base shear strength from the pushover curve and calculating the elastic stiffness factor.

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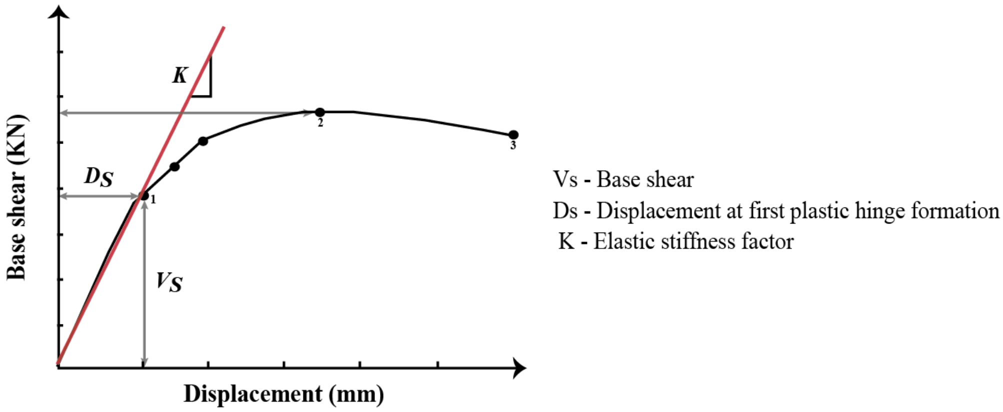

Figure 3. States of pushover curve [21].

The equation for finding the elastic stiffness factor:

$$K = \frac{V_s}{D_s} \tag{1}$$

where V_s is the base shear (first hinge formation in kN, D_s is the displacement at the first plastic hinge formation (in mm), and K is the elastic stiffness factor in kN/mm.

3. RESULTS AND DISCUSSION

In this section, the analysis results of 24 2D models of reinforced concrete dual systems, as well as their ease of operation and graphical user interface, are compared and discussed in graphs and tables for different parameters that affect the elastic stiffness factor, as shown in Table 2, including different shear wall thickness, different number of stories, different span length, and different compressive strength. Comparison and assessment of the reinforced concrete structure with the shear wall is established based on the elastic stiffness factor and the base shear of the dual system.

Table 2. Results of elastic stiffness factor for all of the models

Model No.	Shear wall thickness (mm)	Compressive strength $(f'c)$ kgf/cm^2	Number of stories	Span length (m)	Stiffness factor KN/mm
1	200	250	5	5.5	138.73
2	200	250	5	6.5	127.21
3	200	250	7	5.5	59.33
4	200	250	7	6.5	55.14
5	200	250	10	5.5	29.31
6	200	250	10	6.5	27.88
7	200	280	5	5.5	140.82
8	200	280	5	6.5	132.05
9	200	280	7	5.5	64.33
10	200	280	7	6.5	61.09
11	200	280	10	5.5	33.76
12	200	280	10	6.5	30.19
13	250	250	5	5.5	145.37
14	250	250	5	6.5	136.91
15	250	250	7	5.5	69.04
16	250	250	7	6.5	67.17
17	250	250	10	5.5	36.44
18	250	250	10	6.5	33.20
19	250	280	5	5.5	149.30

20	250	280	5	6.5	139.01
21	250	280	7	5.5	70.14
22	250	280	7	6.5	68.29
23	250	280	10	5.5	38.74
24	250	280	10	6.5	35.31

3.1. The Effect of the Number of Stories on the Elastic Stiffness Factor

The following chart illustrates how the stiffness factor varies across the stories of 5-, 7-, and 10-story buildings with different span lengths. Figure 4 illustrates that the highest stiffness factor, 140.82 KN/mm, was observed in the shorter span length of the 5-story building, while the lowest stiffness factor, 30.19 KN/mm, was observed in the 10-story building with a longer span length. Elastic stiffness decreases by 55% when the number of stories in a building increases from low to mid-rise and by 50% as the building type changes from mid-rise to high-rise. Ngenge et al. [3] showed that increasing the number of stories from 4 to 10 decreased the elastic stiffness factor by 63%. Factors used in this section: Shear wall thickness= 200mm, and compressive strength (f'c)= 280 $\mathrm{kgf/cm^2}$.

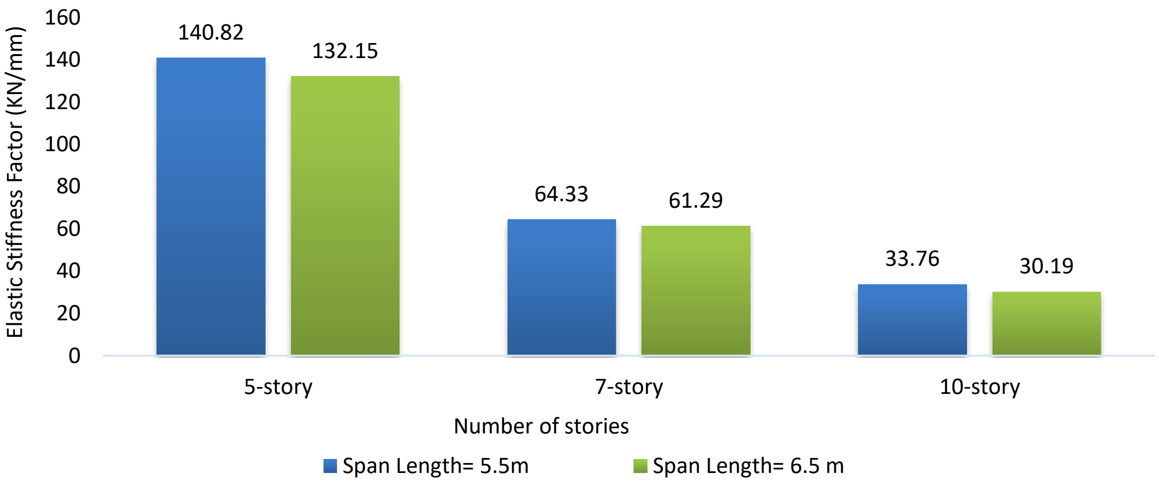

Figure 4. Elastic stiffness factor versus number of stories

3.2. The Effect of Span Length on the Elastic Stiffness Factor

The span length is one of the factors that impact stiffness value. Differences in span length are an appropriate means to show how the stiffness and seismic behavior of the building are affected. Figure 5 illustrates the highest stiffness factor of 138.73 KN/mm appeared in low-rise buildings with span lengths of 5.5 m. On the other hand, the lowest stiffness factor of 27.88 KN/mm appeared in high-rise buildings with span lengths of 6.5 m. Increasing the span length from 5.5 to 6.5 meters in low-rise buildings decreases the elastic stiffness factor by 5%. AlHassan et al. [5] showed that by increasing the span length from 5.5 to 6.5 m, the elastic stiffness factor decreased by 16% for the lowest building. Factors used in this section: Shear wall thickness= 200mm, and compressive strength (f'c)= 250 $\mathrm{kgf/cm^2}$.

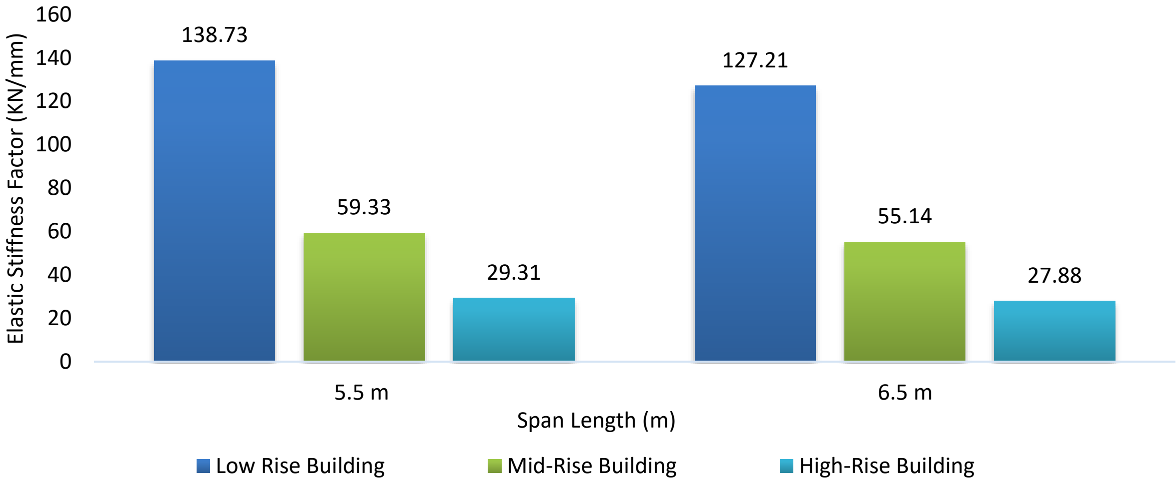

Figure 5. Elastic stiffness factor versus Span length

3.3. The Effect of Compressive Strength on the Elastic Stiffness Factor

Compressive strength ($f'c$) is one of the essential factors that can determine the stiffness of the building. Changes in compressive strength have a positive or negative effect on the stiffness factor. Figure 6 shows how increasing the compressive strength from 250 kgf/cm^2 to 280 kgf/cm^2 increases the stiffness factor from (145.37 to 149.31 KN/mm) equal to a 2.5% increment for a span length of 5.5m. Additionally, when the span length is increased to 6.5 meters, the stiffness factor rises from 136.91 KN/mm to 139.01 KN/mm, representing a 1.5% increase. Factors used in this section: Story number = 5 (low-rise buildings), and shear wall thickness= 250mm.

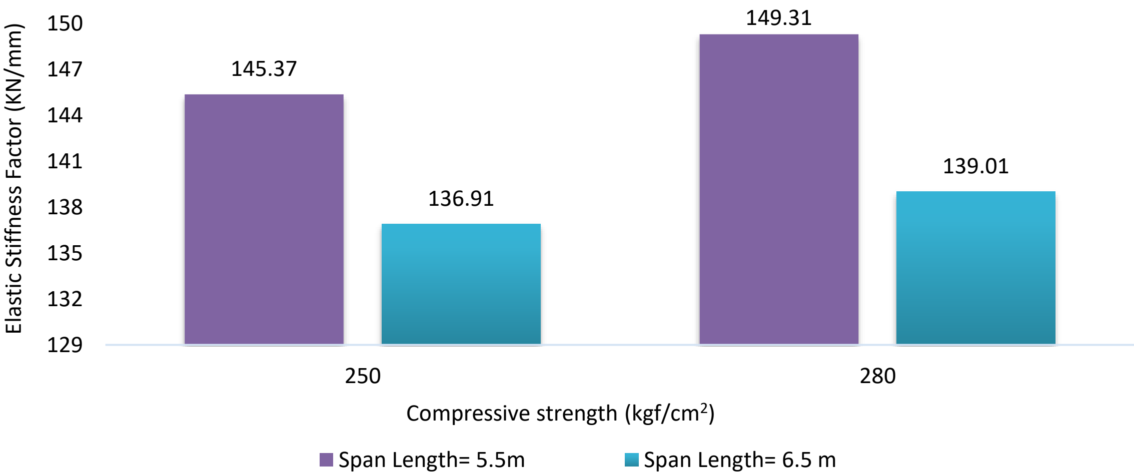

Figure 6. Elastic stiffness factor versus Compressive strength

3.4. The Effect of Shear Wall Thickness on the Elastic Stiffness Factor

This section presents the results of an experiment into how different shear wall thicknesses affect the stiffness factor at different span lengths. The founded stiffness factors with 200 mm shear wall thickness are (140.82 and 132.15 KN/mm) for span lengths of (5.5m and 6.5m), while with a shear wall thickness of 250 mm, the stiffness factors are (149.31 and 139.01 KN/mm) for span lengths of (5.5m and 6.5m). Figure 7 illustrates how the stiffness factor increases with increasing shear wall thickness from 200 to 250 mm. Specifically, it increases by 7% for span lengths of 5.5m and 6% for span lengths of 6.5 m. Factors used in this section: Story number = 5 (low-rise buildings), and compressive strength (f'c) = 280 $\mathrm{kgf/cm^2}$.

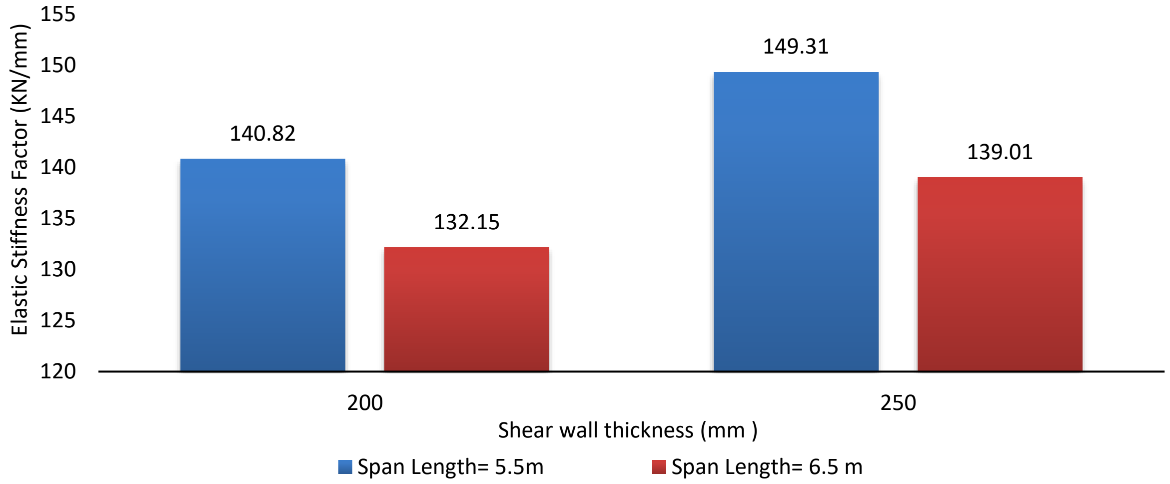

Figure 7. Elastic stiffness factor versus shear wall thickness

3.5. The Effect of Span Length and Number of Stories on Base Shear

This section indicates how the base shear of a dual system varies depending on the number of stories and span length. Figure 8 illustrates how base shear rapidly decreases from (1903 to 774 and then to 580 KN) as stories increase from (5 to 7 and then to 10 stories) for a span length of 5.5 m. The base shear decreases from (1752 to 701 and 490KN) as the number of stories increases from (5 to 7 and then to 10 stories) for a 6.5m span length. When the span length increases from 5.5 to 6.5 meters, the base shear decreases by 8% in low-rise buildings, 9.5% in mid-rise buildings, and 15.5% in high-rise buildings. Maximum base shear was achieved in fewer stories and smaller span lengths. Factors used in this section: Shear wall thickness= 200mm, and compressive strength (f'c)= 250 $\mathrm{kgf/cm^2}$.

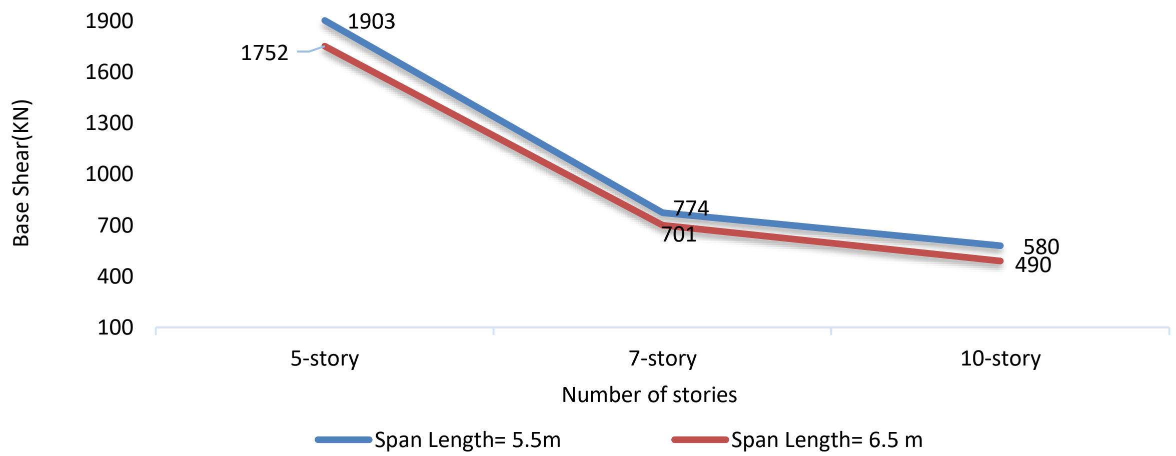

Figure 8. Relation between story number and span length vs base shear

The results achieved in this study are from only buildings with shear walls, and the number of stories used is expected in the study area.

4. CONCLUSION

This study evaluates the elastic stiffness factor and base shear of a two-dimensional reinforced concrete structure with a shear wall (dual system) for various parameters affecting stiffness using a non-linear static (pushover) analysis approach. To determine the impact of the number of stories, span length, compressive strength, and shear wall thickness on the elastic stiffness factor and base shear, 24 ETABS models were analyzed and designed using the equivalent lateral force procedure. Each model's results were compared and assessed. The following is a summary of the study's outcome:

- Studying the parameters that influence stiffness in RC buildings with dual systems is critical for assuring the building's reliability and performance, particularly under seismic and wind loads. Stiffness directly impacts the structure's ability to withstand lateral forces and control deflections, lowering the risk of extreme deformation or collapsing.
- Implementing dual systems in reinforced concrete (RC) structures, combining moment-resisting frames with shear walls, improves flexibility and strength. The moment-resisting frames provide ductility and dissipated energy, whereas shear walls give stiffness and lateral load resistance. This combination increases the structure's performance under gravity and seismic stresses, resulting in more outstanding durability and resistance. Dual systems are wildly successful in high-rise buildings and seismically active areas, where flexibility and strength are required for structural stability.
- Pushover analysis is a fundamental approach to evaluating buildings' non-linear properties.
- Using the pushover method helps to identify story displacement in each story.
- Pushover analysis finds weak points in the building with the help of plastic hinge location.
- Compared to mid-rise and high-rise buildings, the low-rise building was stiffer.
- By changing the number of stories from a low-rise building to a mid-rise building, the stiffness factor decreases by 55%, and by changing the number of stories from a mid-rise building to a high-rise building, the stiffness factor decreases by 50%.
- The span length and stiffness have been observed to be inversely proportionate to each other.
- By raising the span length from 5.5m to 6.5m, the stiffness factor decreases approximately by % 5 for all story numbers.
- The stiffness factor increases by 2% by increasing compressive strength from 250 kgf/cm^2 to 280 kgf/cm^2.
- Increasing the shear wall thickness from 200 mm to 250 mm increases the stiffness factor by 7%.
- When the number of stories increases from 5 to 7 and 7 to 10, base shear immediately reduces. Similarly, base shear reduces when the span length increases from 5.5m to 6.5m.

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