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Original Article

Effect of Steel Bracing on Seismic Performance of Reinforced Concrete Structures

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Abstract *- Steel bracing systems are widely recognized for their effectiveness in improving the earthquake resistance of REINFORCED CONCRETE (RC) frames, especially in high-rise buildings. This study investigates how varying the diameter of steel braces affects the seismic performance of an eight-story REINFORCED CONCRETE (RC) structure, focusing on total lateral displacement, inter-story drift, and the fundamental time period. Using SAP2000 software, a nonlinear static analysis is conducted on an idealized two-dimensional model of the building. The study also evaluates the impact of various bracing configurations on the building's stability. The findings clearly show that adding steel bracing greatly improves a building's response to earthquakes. The fundamental time period had been reduced by 65%, as the maximum inter-story drift had been reduced by 77%, as compared to an unbraced frame. In contrast with the unbraced system, incorporating steel bracing improves structural stiffness and reduces inter-story drift.*

Keywords *- Steel bracing, Sap2000, RC structure, Storey Drift, Pushover analyses.*

1. Introduction

With the population growing and residential land remaining constant, cities are becoming more crowded due to migration from rural areas. As a result, vertical construction is the most practical way to provide sufficient housing. Over the past few decades, the rapid growth of urban populations has led to the urgent need for more high-rise buildings [1]. Modern structures are now designed to be taller in order to maximize usable space. However, this shift introduces a critical challenge for engineers in managing lateral forces. As buildings rise to greater heights and become more slender, their susceptibility to large horizontal forces increases, making the control of lateral loads a primary consideration during the design process [2].

The lateral displacement of a building primarily depends on its stiffness. Typically, stiffer structures exhibit lower lateral displacement. Structures that are stiffer usually undergo less lateral displacement. As buildings increase in height, they also become more vulnerable to wind effects, in addition to seismic activity [3]. During an earthquake, structural members deform under imposed ground motion, which in turn generates internal forces within the building. These internal forces lead to apparent displacements. In recent years, there has been significant improvement in earthquake engineering, with numerous studies focusing on understanding how structural components respond to seismic loading [4-7].

1.1. The Effect of Earthquakes

Earthquakes are among the most sudden and destructive natural disasters [8]. In recent years, major seismic events have caused the deaths of thousands of people each year [9]. The violent shaking of the ground during an earthquake can generate secondary disasters such as landslides, flash floods, and powerful ocean waves. During these actions, buildings are particularly exposed to damage. Earthquakes result from the sudden release of accumulated energy along fault planes, creating seismic waves that move through the Earth's layers. These energy waves travel through the ground and strike building foundations, turning into seismic loads that a structure must absorb and resist.

The lateral forces that a building experiences during an earthquake are influenced by several key factors. These include the strength and magnitude of the earthquake, how far the building is from the epicenter, and the characteristics of the building itself, such as its structural design and total weight of building.

The lack or inadequacy of structural systems has played a significant role in the destructive collapse of buildings during recent earthquakes. For example, during the 2023 Turkey-Syria earthquake, numerous mid- and high-rise reinforced concrete structures suffered severe failure, primarily due to inadequate lateral strength. This failure led to the tragic deaths of over 50,000 people. Similarly, the 2021 earthquake in Haiti exposed major weaknesses in buildings with either no bracing or poorly designed reinforced concrete frames, resulting in structures experiencing soft-story collapses and excessive lateral movement. These disasters underscore the critical importance of implementing robust lateral load-resisting systems, particularly in developing countries where seismic design standards are frequently not fully enforced.

Lateral displacement and inter-story drift are essential factors in designing buildings to withstand earthquakes [10]. In tall buildings, especially those exceeding 25 stories, rigid frame systems by themselves are usually insufficient to withstand lateral loads because column bending leads to excessive deformation. To address this, engineers can enhance the building's overall stiffness by integrating bracing elements or shear walls into the frame, allowing it to better absorb and transfer the forces caused by seismic activity.

1.2. Braced Frame System

Bracing elements are recognized not only for their structural efficiency but also for their aesthetic value. Bracing systems are generally classified into two main types: concentric and eccentric. Concentric braces are joined directly at the intersection of beams and columns (Figure 1), whereas eccentric braces are connected to the beam at a point offset from the joint. Over the last 50 years, numerous investigations using experimental methods and numerical modelling have been carried out to better understand the behavior of Eccentrically Braced Frames (EBFs) and to develop appropriate design strategies for their use in practice [11].

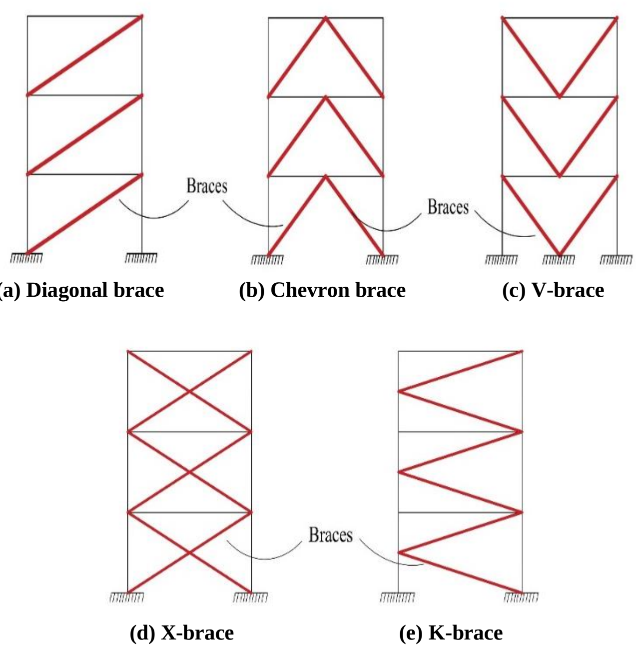


Fig. 1 Configuration types of concentric bracing frames [12]

Conventionally, bracing has been a specialized steel system, but its use has expanded to reinforced concrete structures where it helps resist lateral forces caused by earthquakes [13]. Recently, large-scale external mega-bracing systems that span multiple bays and floors have been introduced, creating structures that are both structurally efficient and visually attractive. Bracing systems can be categorized into two main groups: those located inside the building and those placed externally [14].

1.3. Previous Studies on Bracing Members

Numerous studies have been conducted over the years to understand how buildings respond during earthquakes. Researchers have examined how different parts of a building behave when subjected to an earthquake, how the materials used affect the building's strength, and how to design structures that can better withstand seismic forces. Lee and Taip (2024) highlight the continuous advancements and importance of steel bracing in reinforced concrete structures. Their study compared concentric and inverted-V bracing systems in medium-rise reinforced concrete and steel frames, employing nonlinear pushover and time-history analyses. Khan and colleagues (2023) investigated the use of eccentric steel braces combined with column jacketing in reinforced concrete frames in Pakistan. The study found that these retrofitting techniques increased the base shear capacity by 45%. In addition, Sadeghpour and Özay (2025) employed the FEMA P695 procedure to evaluate reinforced concrete frames strengthened with steel bracing, confirming notable improvements in both collapse prevention and drift reduction.

Al-Safi et al. [15] explored how various bracing systems influence the structural behavior of steel buildings subjected to wind and seismic forces. In their investigation, Ahiwale et al. [16] found that incorporating bracing systems substantially enhanced the earthquake resistance of reinforced concrete structures. Notably, the presence of bracing resulted in a significant reduction in inter-story drift compared to unbraced frames, underscoring the effectiveness of these structural elements in controlling lateral movement during seismic events. Yassin and Sadeghi [17] conducted a nonlinear static analysis to assess the impact of different bracing configurations on the seismic performance of steel frames. Their findings showed that frames equipped with X-bracing offered the highest level of seismic resistance. The study also explored the influence of brace placement, testing both mid-span and two-span configurations.

Different studies have investigated how various bracing arrangements affect the response of reinforced concrete frames during earthquakes. These studies found that adding braces can contribute to reducing floor drift and lateral displacement, although some have not explored how the size of the braces or what happens after the building starts to deflect permanently. Other research focused on strengthening buildings using steel braces and fiber-reinforced materials, showing better energy absorption and strength against lateral forces. However, these studies mostly focused on medium-height buildings. Some studies have also examined how steel braces improve strength and flexibility in shorter buildings, but these studies were limited to structures no higher than three stories. Additionally, different brace configurations have been tested using dynamic analysis; however, they often didn’t consider how varying brace sizes or behaviour beyond the elastic limit might influence the results.

1.4. Shear Walls and Bracings

Compared to conventional retrofitting techniques such as masonry shear walls, additional concrete layers, or base isolation, steel bracing systems are often preferred due to their simplicity in execution and relatively lower cost. There are two main strategies used to improve the seismic performance of existing buildings. One approach involves strengthening the structure as a whole by incorporating load-resisting elements such as steel braces or shear walls, which improve its overall stability. The other method targets specific weak points in the building, strengthening them through techniques like concrete or steel jacketing, or by using fiber-reinforced polymers [18]. Shear walls greatly increase the lateral stiffness of low-rise buildings [19].

1.5. Influence of Section Type

Braces with hollow circular and square cross-sections tend to perform better under cyclic loading when their slenderness and width- or diameter-to-thickness ratios are reduced. However, circular braces generally showed superior hysteretic behavior compared to square sections [20]. In structural applications, rolled steel sections are frequently adopted as support braces in buildings. Single-angle sections, as shown in Figure 2(a), are generally used as ties. The configurations shown in Figure 2(b) and Figure 2(c), which consist of double-angle sections, serve dual purposes. They can serve both as ties and as elements for structural reinforcement. The rolled steel bracing illustrated in detail (d) offers strong structural capabilities. However, using it in an X-shaped configuration can be problematic due to difficulties in placing a suitable gusset plate at the intersection. Compared to star-shaped sections, which are typically used for long or heavily compressed members, rolled steel demonstrates superior performance. In detail (e), twin-angle sections are shown functioning as connectors for lacing or batten systems. An H-section, or the I-section depicted in Figures 2(f) and (g), performs well in structural systems where the member’s depth is positioned perpendicular to the plane of bracing [21].

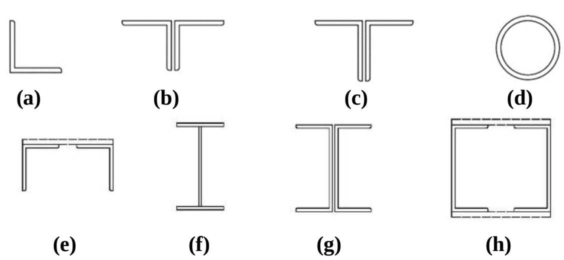


Fig. 2 Bracing sections

As illustrated in Figure 2(h), double-plane gussets are connected to the flanges. Hollow structural sections are widely used in engineering because of their excellent strength-to-weight ratio and enhanced resistance to twisting forces [22].

Reinforced concrete frames strengthened with steel braces have gained extensive acceptance for their ability to enhance a building’s strength, rigidity, and capacity to absorb seismic energy. Although many studies have examined the role of bracing in low and mid-rise buildings, there is a notable Gap in comprehensive research focused on how different bracing configurations and brace diameters affect the seismic behavior of high-rise reinforced concrete structures. Additionally, few investigations have applied nonlinear static analysis, a method that more accurately reflects how buildings respond during earthquakes, to assess these factors. This study seeks to address this gap by thoroughly evaluating how various brace arrangements and sizes affect the seismic performance of RC frames, aiming to provide useful guidance for designing safer and more resilient high-rise buildings in earthquake-prone regions.

This research aims to fill the existing gap by examining how different bracing configurations and brace diameters affect the seismic behavior of an eight-story reinforced concrete building. A detailed two-dimensional model was created using SAP2000 software and analyzed through nonlinear static (pushover) methods. The study focused on key seismic indicators such as lateral displacement at each floor, inter-story drift, and base shear to assess how various bracing sizes impact structural response. To reflect practical design considerations, the braces were positioned along the building’s façade, aligning with typical architectural requirements.

The novelty of this study lies in investigating brace diameter as a variable, a factor often assumed constant in prior research. It also examines an eight-story building, extending beyond the typical focus on three to five-story structures found in existing literature. Moreover, the use of nonlinear static analysis provides a more realistic simulation of post-elastic seismic behavior, an approach often overlooked in comparable studies. Previous research has analysed braced steel frames using linear static methods, without exploring the effects of brace diameter. In contrast, other studies have focused on specific bracing types in mid-rise frames, but have not considered façade placement or employed nonlinear analysis. In contrast, this study’s novelty is highlighted by demonstrating that façade bracing with optimized diameters can reduce the fundamental time period by up to 65% and significantly decrease inter-story drift. By addressing these neglected factors, this research provides practical insights for engineers and designers seeking to enhance the seismic performance of high-rise reinforced concrete buildings through strategic bracing design.

2. Case Study

2.1. Description of Buildings

An eight-story reinforced concrete (RC) building was selected to assess its seismic performance both in its original state and after retrofitting with three different bracing configurations, each configuration including varying brace diameters. Figure 3 represents the three different bracing configurations applied to the frames. Both the original and retrofitted structures consist of five bays. The elevation view of the building is shown in Figure 4. To strengthen the existing structure, concentric steel bracing was added, specifically using diagonal bracing systems as the preferred form of concentric bracing. The material properties used in the analysis are detailed in Table 1. Following this, a pushover analysis was performed to assess how the reinforced concrete frame behaves under seismic loads, both before and after the installation of the concentric steel braces. Each story has a height of 3.2 meters. Seven cases of the building were evaluated:

Case 1 represents the original reinforced concrete (RC) building. Cases 2 through 7 involve strengthening the existing RC structures by adding three different types of steel bracing. Each of these bracing configurations was evaluated with outer brace diameters of 15 cm and 20 cm to determine their effectiveness.

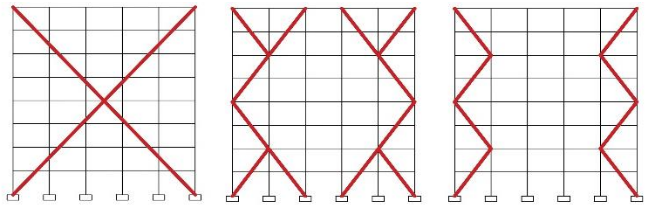
The structural frame was designed using columns with square cross-sections and beams with rectangular cross-sections (Table 2). For the steel elements, standard hollow pipe sections were selected, with two different brace outer diameters (D) of 15 cm and 20 cm used in modelling each braced frame configuration. During the modelling of the frame, all applicable loads were considered, such as dead loads and live loads. The live load factor (ψEi) was appropriately set at 0.3, and the frame was designed without any structural irregularities. For consistency, the brace thickness was maintained at 6 mm across all configurations.

Table 1. Material properties

Material	Properties
Steel Minimum yield strength	250 Mpa
Young's modulus of concrete, E	25000 N/mm^2
The modulus of elasticity for steel	2×105 N/mm^2.
Density of reinforced concrete	25 kN /m^3
Poisson's ratio of ν	0.3
compressive strength of concrete	21 N/mm^2

2.2. The Structural Analysis

This research evaluates the earthquake resilience of an eight-story reinforced concrete structure using SAP2000 version 23.3.1, a powerful structural analysis and design tool developed by Computers and Structures, Inc. (CSI), based in the United States. SAP2000 supports a wide range of analysis types, including static, dynamic, linear, and nonlinear approaches. For this study, the software's nonlinear static (pushover) analysis feature was employed to realistically capture how the building responds to seismic forces. The program's advanced capabilities, such as automatic pushover curve generation, hinge modeling aligned with FEMA standards, and precise treatment of bracing components, made it especially effective for assessing how various bracing layouts and brace sizes impact the seismic behavior of reinforced concrete frames.



Configuration 1 **Configuration** 2 **Configuration** 3

Fig. 3 braced frames with three configurations

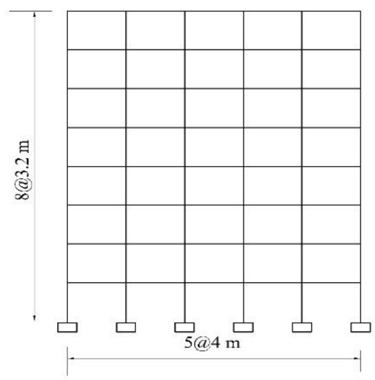


Fig. 4 Typical floor elevation of the selected building

Table 2. Dimensions and the details of the Columns and beams in cm.

Story No.	Column size	Beam size
1	50 × 50	60 × 40
2	50 × 50	60 × 40
3	50 × 50	60 × 40
4	50 × 50	60 × 40
5	40 × 40	60 × 40
6	40 × 40	60 × 40
7	40 × 40	60 × 40
8	40 × 40	60 × 40

2.3. Pushover Analysis

Pushover analysis is a nonlinear static approach used to evaluate how a structure responds to increasing lateral forces. This method applies horizontal loads incrementally until the building reaches its failure point, capturing the full range of deformation. The relationship between base shear and roof displacement is plotted to create a "capacity curve," offering insight into the structure's ability to withstand seismic demands and its potential for deformation before collapse. As shown in Figure 5, this analysis helps engineers understand the strength and flexibility of a building when subjected to earthquake-like forces.

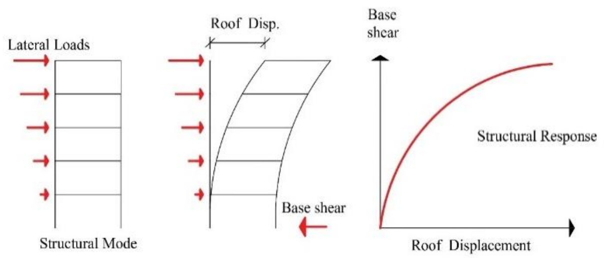


Fig. 5 Static estimation employed in pushover analysis

Figure 6 presents the relationship between applied force and resulting deformation in the structural element. The curve begins at Point A, which represents the structure in its original, unloaded state. As loading increases, the element begins to yield at Point B, indicating the onset of inelastic behaviour. At Point C, the element reaches its peak (or nominal) strength. This is the maximum it can resist before performance begins to drop. The curve's decline from Point C to Point D illustrates the initial failure phase, where the element starts to lose strength. However, even after this point, the structure retains some capacity. The section between Points D and E demonstrates that the element remains capable of bearing gravity loads, albeit with reduced effectiveness. The structure can no longer support the gravity load once it exceeds Point E, which represents the maximum deformation capacity.

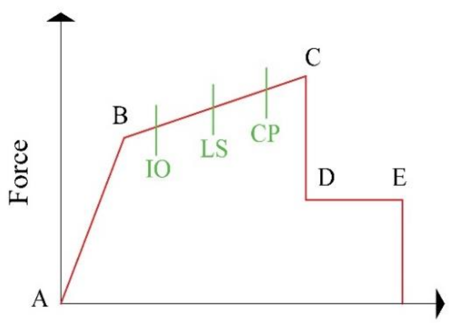


Fig. 6 Curve force Vs Deformation

3. Results and Discussion

Earthquakes remain a major risk to the structural integrity of buildings, especially in areas where construction quality is inadequate or design codes are technically deficient. Such seismic events frequently lead to significant lateral displacements, excessive story drift, and sometimes even the complete failure of reinforced concrete frames due to inadequate or improper detailing. These challenges emphasize the urgent need for effective methods to strengthen structures against earthquakes. Among the various techniques available, steel bracing systems have proven to be a dependable approach for increasing lateral stiffness, enhancing energy absorption, and improving the overall stability of RC buildings. By limiting horizontal displacement and contributing to the uniform distribution of seismic forces, bracing presents a practical, efficient, and economical strategy for both newly built structures and the rehabilitation of existing ones.

As mentioned before, the study examined both the unbraced (bare) reinforced concrete frame and frames strengthened with three different diagonal bracing configurations. Key structural response parameters, such as capacity curves, story displacement, and drift, were analyzed and compared between the original and retrofitted models. The comparative outcomes of these analyses are discussed in detail below.

3.1. Frame Capacity

The capacity curves (pushover analysis results) from nonlinear static analysis for three different cases are shown in Figs. 7 and 8. These graphs display the results for various brace diameters employed in the investigated structures, including the original frame and three distinct bracing configurations.

The frame without braces exhibited the lowest lateral stiffness among all configurations, resulting in the maximum roof displacement under the highest possible base shear force. According to this maximum base shear, concentrically braced buildings (Configuration-2) were the most notable case, exhibiting the highest stiffness and the lowest roof displacement.

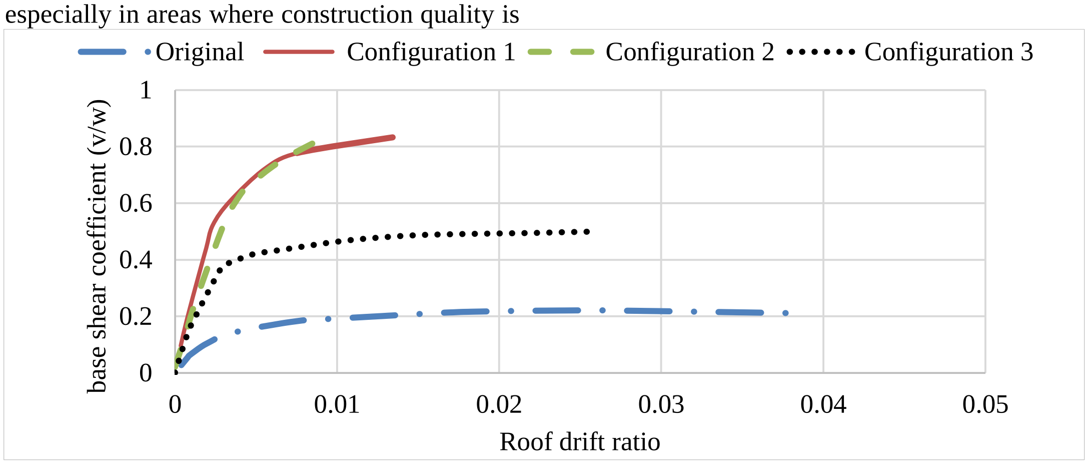


Fig. 7 Capacity curves of the original and braced frames from pushover analysis: when D = 15cm

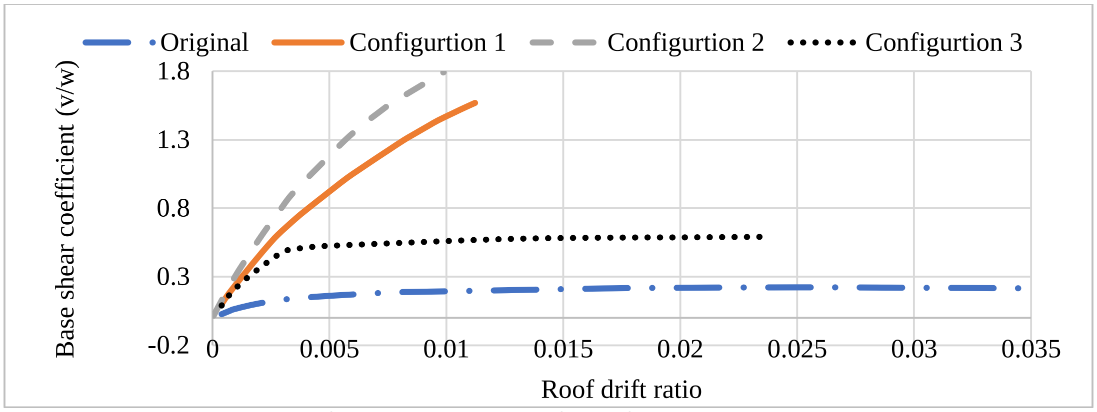


Fig. 8 Capacity curves of the original and braced frames from pushover analysis: when D = 20cm

3.2. Global Displacement

The unbraced frame experienced a total displacement of 1.1 meters, whereas every braced configuration demonstrated a significant decrease in lateral displacement. Configuration 2 showed the best performance, reducing displacement to 0.28 meters with a brace diameter of 20 cm. A reduction of approximately 75% in storey displacement at the top storey level was detected as compared with the bare frame. As shown in Table 3, Configuration 3 exhibited a displacement of 0.49 meters with a brace diameter of 15 cm. When the brace diameter was increased to 20 cm, the displacement decreased significantly to 0.29 meters (Figures 9 and 10).

Table 3. Global displacement of the braced frames in (m)

Frame description	Global displacement (D=15cm)	Global displacement (D=20cm)
Configuration 1	0.74	0.68
Configuration 2	0.3	0.28
Configuration 3	0.49	0.29

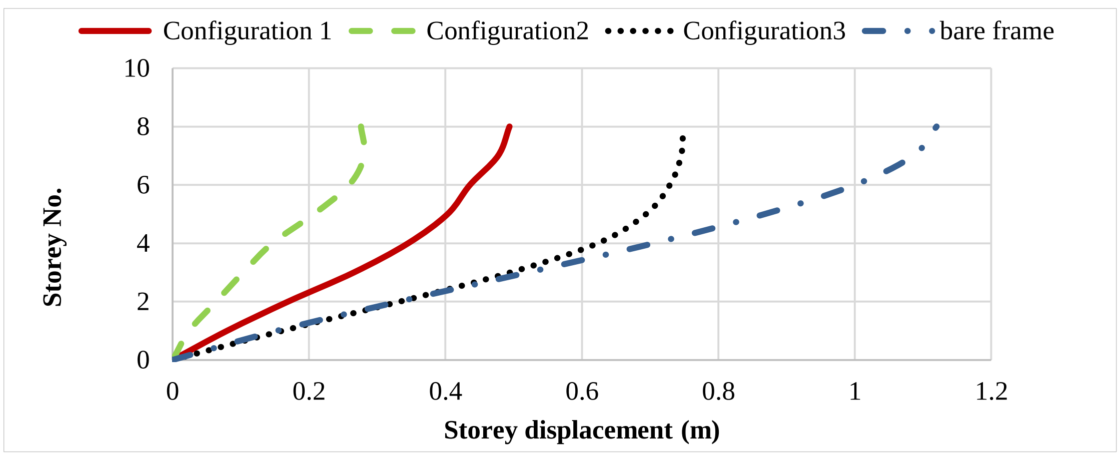


Fig. 9 Comparison of the displacement versus storey number for D = 15 cm

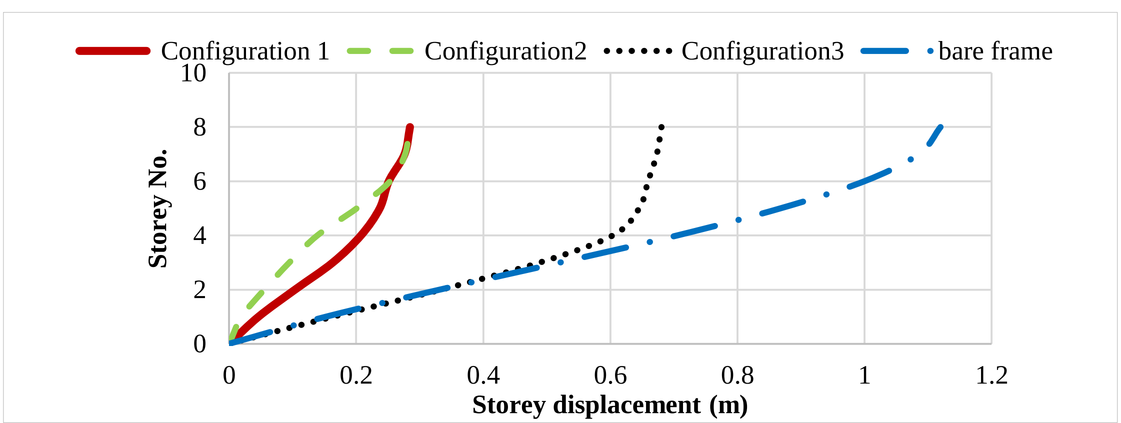


Fig.10 Comparison of the displacement versus storey number for D = 20 cm

3.3. Storey Drift

Allowable story drift, often denoted as (Δa), represents the maximum permissible lateral displacement or drift that a building or structure can undergo under specified conditions, typically during strong wind or an earthquake. Acceptable story drift is a crucial design criterion in structural engineering, ensuring a building's safety and functionality. Design codes commonly specify the allowable story drift as $\Delta_a = 0.02h$, When h = story height, the analysis has shown that configuration-2 with a brace diameter of 20 cm demonstrates a superior response, as evidenced by reduced inter-storey drift when compared to both the bare frame and the other configurations, as shown in Figures 11 and 12. The story height is 3.2 meters. The allowable story drift is calculated as 0.02 × h, which equals 0.02 × 3.2 = 0.064 meters (or 6.4 cm). This value was used as the basis for evaluating drift performance in this study.

Configuration-2, when assessed, shows that the structural drift remains within this permissible limit. This compliance ensures that Configuration-2 maintains structural integrity and safety standards, preventing excessive deformation under load conditions and thus avoiding potential damage or failure.

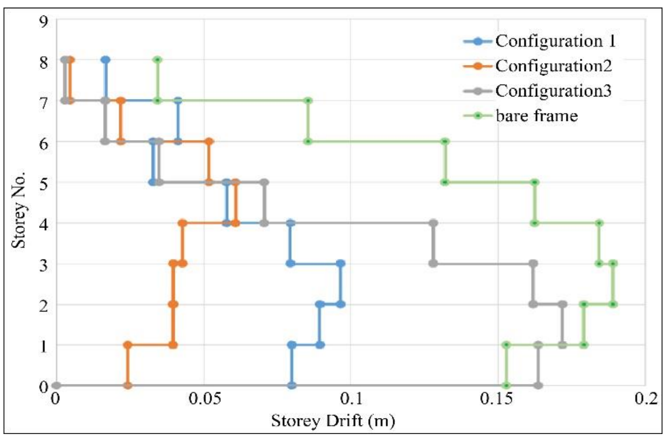


Fig.11 Comparison of the storey drift versus storey number for D = 15 cm

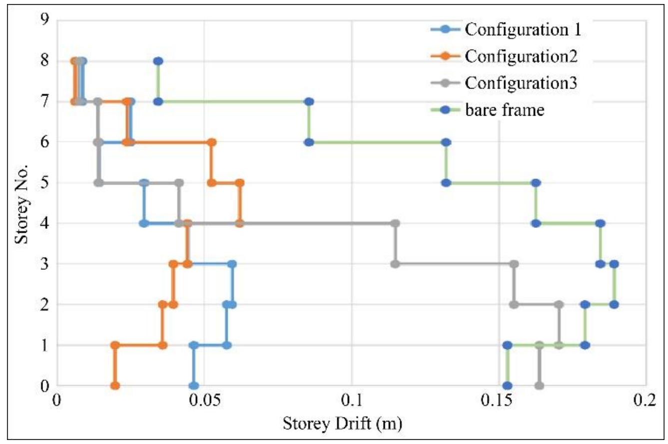


Fig. 12 Comparison of the storey drift versus storey number for D = 20 cm

3.4. Fundamental Time Period

The fundamental time period of a structure refers to how long it takes to complete one full vibration cycle. For the unbraced (bare) frame, this period was recorded at 1.53 seconds, reflecting a slower vibration rate due to its relatively flexible form and lack of lateral support. Once steel bracing was introduced, the period dropped sharply to 0.54 seconds, indicating that the structure became significantly stiffer and vibrated at a faster rate. This reduction was especially pronounced when using bracing with a 20 cm diameter, which significantly strengthened the structure and shortened the vibration cycle. The incorporation of bracing effectively increased the frame's rigidity, resulting in improved stability and a quicker dynamic response, as illustrated in Figure 13.

Longer time periods, such as that of the unbraced frame, indicate a more flexible system, which tends to experience greater lateral movement during earthquakes, especially those involving long-period ground shaking. On the other hand, a braced frame with a shorter time period reacts faster, resists lateral forces more effectively, and performs better under seismic loading.

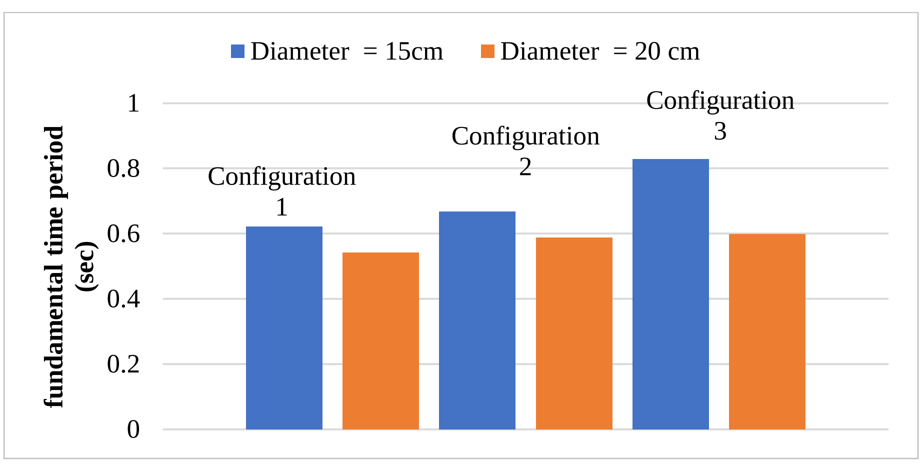


Fig. 13 fundamental time period

The enhanced outcomes observed in this research can be due to several important factors. Unlike many earlier investigations that relied on fixed or standard brace sizes, this study explored varying the brace diameter and optimizing its arrangement, which led to more efficient force distribution and increased structural rigidity. Furthermore, the focus on applying bracing along the building's façade, an aspect often neglected in previous investigations, demonstrated significant effectiveness in limiting lateral movement while preserving the internal usability of the structure. Another key distinction lies in the use of nonlinear static (pushover) analysis rather than the linear techniques typically employed in prior research, enabling a more precise representation of the building's behavior beyond the elastic range during earthquakes. Compared to earlier studies that focused on low to mid-rise buildings and did not consider brace sizing or façade bracing effects, this work provides a more advanced and realistic approach to seismic modeling.

4. Conclusion

As many researchers have reported their results regarding structural systems, one may choose to use a structural system for the preliminary design depending on a few factors, including the building's height, seismic zone, wind loads, etc. Here, the bracing system, based on advanced engineering principles, provides strong performance. The bracing elements have played a valuable role in enhancing the lateral force resistance system. The presence of bracing elements results in a notable reduction in lateral displacement when compared to a bare frame. In conclusion, it is crucial to emphasize that this research's outcomes are the result of extensive simulations conducted on an 8-story structure.

This study explores how buildings equipped with bracing systems behave under seismic forces. The findings clearly indicated that adding steel bracing greatly improved the structure's seismic response. The maximum inter-story drift was lowered by 77%. Among all the configurations tested, Configuration-2 demonstrated the most effective performance, showing the smallest overall lateral displacement for both 15 cm and 20 cm brace diameters. The structure with the largest bracing diameter exhibits the smallest lateral displacement. The main goal of this study was to demonstrate that variations in the bracing diameter of the structural system positively affected its performance. Initially, the frame without bracing had a fundamental time period of 1.53. However, once the bracing was applied, the frame's fundamental time period significantly decreased to 0.54, demonstrating the effectiveness of the bracing in enhancing the structural stability.

When the brace diameter in the building's structural system was increased from 15 cm to 20 cm, there was a notable improvement in its performance under lateral loads. Specifically, the roof drift ratio decreased significantly, demonstrating enhanced stability and stiffness. The larger diameter braces provided greater resistance to lateral forces, which in turn limited the amount of displacement experienced by the roof during such seismic excitations.

Based on the outcomes observed, structural engineers are encouraged to incorporate steel bracing into the design of multistory reinforced concrete buildings in seismic regions. Careful attention should be given to the size and placement of braces, especially along the façade, as these factors play a crucial role in enhancing lateral stiffness and the building's ability to dissipate seismic energy. For existing structures, steel bracing provides an economical and effective retrofit solution that avoids extensive demolition or reconstruction. Future research could build on this work by employing three-dimensional modeling, considering nonlinear material behavior, and evaluating performance under dynamic seismic loading using time history.

To determine the most effective steel bracing system for a building, it is important to incorporate and evaluate a variety of steel brace configurations. By examining different setups, engineers can better understand how each arrangement performs under seismic loads, helping to identify the design that offers the best combination of strength, stability, and cost-efficiency. This approach ensures that the chosen bracing system not only enhances the building's safety but also aligns with practical construction and architectural considerations.

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