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RESEARCH

Estimation of elastic and inelastic seismic behavior of reinforced concrete framed structures

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Abstract

The paper titled "Estimation of Elastic and Inelastic Seismic Behavior of Reinforced Concrete Framed Structures" aims to investigate the seismic performance of reinforced concrete framed structures using both elastic and inelastic analysis methods. The study focuses on developing a reliable and accurate method to estimate the seismic behavior of such structures under different levels of seismic loading. The research includes a detailed literature review of the relevant seismic codes and standards, as well as past studies on the seismic performance of reinforced concrete structures. The analysis methods used in the research include finite element modeling and nonlinear static and dynamic analysis. The study investigates various factors that can influence the seismic performance of reinforced concrete framed structures, including structural geometry, material properties, reinforcement detailing, and seismic hazard levels. The research aims to provide insights into the effects of these factors on the structural response and failure modes under different seismic loads.

Keywords Inelastic · Seismic · Concrete · Frame structure

Introduction

Background: Reinforced concrete buildings (RCC) are commonly used in seismically active regions due to their ability to withstand the horizontal forces generated by earthquakes (Bolea, 2016). The design of these buildings must consider the dynamic nature of earthquakes and the loads they impose (Del Carpio et al., 2016). The introduction provides an overview of seismic hazards, design philosophy, and codes, as well as highlights the key features that make RCC buildings seismically resistant (Mazza, 2015).

Reinforced concrete buildings (RCC) are widely used in seismically active regions due to their ability to withstand large horizontal forces caused by earthquakes (Saha et al., 2020). The design of these buildings must account for the dynamic nature of earthquakes and the various types of loads that the building will be subjected to during an event (Sharafi & Shams, 2020). The introduction of an RCC building design subjected to earthquake loads should include a brief overview of the seismic hazard in the area where the building will be constructed, the design philosophy and codes used, and a summary of the key features of the building that make it seismically resistant (Tehrani et al., 2018). Additionally, it should also provide the background and motivation for the study and the objective of the design (Lu et al., 2021).

An RCC building subjected to earthquake loads typically follows a performance-based design approach, which aims to ensure that the building can withstand the expected levels of ground motion while maintaining an acceptable level of damage (Eren et al., 2019). This approach typically involves the use of seismic hazard analysis to determine the expected levels of ground motion at the site, and the use of nonlinear static or dynamic analysis to evaluate the building's response to these motions (Zhai et al., 2015).

A braced frame is a type of seismic-force resisting system (SFRS) that is commonly used in low-to-medium-rise buildings to resist the forces caused by earthquakes. It consists of a combination of diagonal steel braces and vertical steel or concrete elements, such as columns and walls, designed to provide strength and stiffness in the direction perpendicular to the plane of the building (Marius, 2013).

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Compared to other seismic-force resisting systems, such as moment frames and shear walls, braced frames provide a high level of seismic resistance and are relatively simple to design and construct. They are also well suited for buildings with limited architectural flexibility (Chaulagain et al., 2014). However, they may require more space than other systems and may not be suitable for buildings with high seismic hazards.

Motivation: The motivation for this study stems from the need to enhance our understanding of RCC buildings' behavior subjected to earthquake loads. By investigating the structural behavior of a braced frame system, we aim to contribute valuable insights to the field of seismic design and provide guidance for designing safer and more resilient structures.

Objectives: This work aims to investigate the structural behavior of a reinforced concrete building using a braced frame system under seismic loads. The objectives of the present study consist of studying the seismic behavior of a reinforced concrete building using a braced frame system through software simulation and analyzing the effect of different design parameters, such as brace configuration, brace spacing, and brace strength, on the seismic performance of the building.

The primary objectives of this study are twofold:

1. To analyze the seismic behavior of a reinforced concrete building utilizing a braced frame system and shear wall through software simulation.
2. To investigate the impact of various design parameters, such as brace configuration, brace spacing, brace type, location of the bracing and shear wall, and combination of the different bracing patterns along with shear wall on the seismic performance of the building.

Contribution

This research significantly contributes to understanding the structural behavior of RCC buildings using braced frame systems under seismic loads. Examining the impact of design parameters on the building's seismic performance provides valuable insights for structural engineers and architects in designing more robust and resilient structures in seismically active areas.

Organization

The paper is organized as follows:

- "Introduction" section provides an introduction to the background, motivation, objectives, and contribution of the study.
- "Literature review" section reviews the relevant literature and previous research in the field of seismic design and braced frame systems.
- "Methodology" section outlines the methodology, including the software, model development, and analysis techniques.
- "Results and Discussion" section presents the results and analysis of the seismic behavior of the reinforced concrete building with a braced frame system.
- Finally, "Conclusions" section offers a conclusion summarizing the key findings and their significance, emphasizing the contribution made by this research.

Literature review

The following work is related to different literature reviews:

RCC building analysis

Li et al. (2018) employed nonlinear dynamic analysis to assess the seismic behavior of mid-rise RCC buildings. Their study incorporated material nonlinearity and considered different ground motion records to evaluate the structural response. The findings emphasized the significance of incorporating ductile detailing and appropriate seismic design parameters to enhance the building's performance.

Furthermore, the utilization of innovative techniques in RCC building analysis has gained attention. Zhou et al. (2020) explored the use of fiber-reinforced polymers (FRP) in strengthening existing RCC buildings. Through experimental testing and numerical simulations, they demonstrated the effectiveness of FRP strengthening in improving the seismic performance and overall structural integrity of the buildings.

Additionally, the incorporation of advanced analysis methods, such as response spectrum analysis and pushover analysis, has been studied extensively. Dutta (2001) conducted a comprehensive investigation on the seismic assessment of tall RCC buildings using response spectrum analysis. Their research focused on evaluating the building's dynamic response and determining the design forces required for effective seismic design.

Marius (2013) conducted a study on the seismic behavior of RCC buildings in Turkey. They found that RCC buildings exhibited good seismic resistance, but that their structural performance could be improved by optimizing the reinforcement details and concrete mix design.

Sivakumar et al. (2023) analyzed the behavior of RCC buildings under wind loads. They found that the use of circular shapes in the building design provided better wind resistance compared to rectangular shapes.

He et al. (2015) conducted a numerical study on the behavior of RCC buildings under fire conditions. They found that the fire resistance of RCC buildings could be improved by using higher performance concrete and increasing the thickness of the fire-resistant layer.

Padol and Talikoti (2015) conducted a study on the seismic behavior of RCC buildings with different lateral load-resisting systems. They found that RCC buildings with a reinforced concrete frame provided the best seismic resistance compared to other systems such as steel frames and masonry walls.

Rana and Raheem (2015) analyzed the behavior of RCC buildings subjected to blast loads. They found that the use of high-strength concrete and appropriate reinforcement details could significantly improve the blast resistance of RCC buildings.

Kaveh et al. (2020) when comparing the performance of various algorithms for optimizing reinforced concrete (RC) structures, which usually contain a large number of design variables and a large search space, the ECBO algorithm outperforms the EVPS and PSO algorithms. The ECBO algorithm exhibits better search capabilities compared to EVPS and PSO algorithms, allowing it to search for a better solution space and produce better results.

Kaveh and Ardalani (2016) the creation of strong rocks using the ECBO algorithm shows higher performance than the designs created with the Big Bang-Big Crunch (BB-BC) algorithm. Further research shows that both the main operational objectives and the design to reduce CO_2 emissions can be achieved in practice at reasonable costs.

Kaveh et al. (2013) the optimization of the design included 35 designs with parameters related to geometry, rock level, and support type. The seismic response of the retaining wall is commonly analyzed using Mononobe–Okabe analysis to determine the overall dynamic lateral pressure. Principle-based numerical simulations show that it is effective in solving the current complex multi-objective optimization problem. The results from the logs prove the framework's ability to solve efficiency-enhancing problems.

Kaveh (2017) the book introduces new metaheuristic optimization algorithms and demonstrates their applications to solve optimization problems in civil engineering. This book offers practical advice on how to use advanced algorithms to solve various optimization problems encountered in civil engineering projects.

These findings suggest that RCC building analysis is a crucial aspect of the design and construction of these structures, as it provides valuable information for optimizing their performance under various loads and conditions. Further research is needed to enhance the understanding of RCC building behavior and to develop more effective design and construction methods for these structures.

Response spectrum analysis in buildings

Bhatt and Bento (2014) investigated the application of response spectrum analysis in the seismic design of steel moment-resisting frames. They proposed an improved method to determine the design spectrum, considering the effects of soil conditions and structural characteristics. The study demonstrated the significance of accurate spectrum selection for reliable seismic design of steel moment frames.

Azad and Abd Gani (2016) conducted a comparative analysis of different methods for response spectrum generation in the design of high-rise buildings. They evaluated the performance of spectrum-compatible accelerograms, recorded accelerograms, and synthetic accelerograms. The study highlighted the benefits and limitations of each method, aiding engineers in selecting the most appropriate approach for their specific design requirements.

Chiou and Youngs (2014) investigated the influence of ground motion duration on the response spectra of mid-rise buildings. Through a series of numerical analyses, they demonstrated the significant impact of ground motion duration on spectral acceleration values, particularly in the long-period range. The findings emphasized the need to consider ground motion duration in selecting and scaling design response spectra.

Hakim et al. (2014) conducted a study on the effectiveness of response spectrum analysis in predicting the seismic response of buildings. They found that response spectrum analysis was a useful tool for estimating the seismic response of buildings and that it provided a good approximation of the actual response when the ground motion characteristics were well understood.

Tahghighi and Rabiee (2015) conducted a numerical study on the influence of soil-structure interaction on the response spectrum analysis of buildings. They found that the inclusion of soil–structure interaction in the analysis could significantly affect the predicted seismic response and that it was crucial to consider this interaction in the analysis.

Ferrero et al. (2016) analyzed the performance of various structural systems under seismic loads using response spectrum analysis. They found that the seismic performance of buildings with different structural systems could be effectively compared using this analysis method.

Abate and Massimino (2017) conducted a study on the use of response spectrum analysis in the design of tall buildings. They found that this analysis method provided valuable information for the design of tall buildings, especially about the selection of appropriate seismic-resistant systems.

Goda et al. (2015) conducted a study on the effect of soil conditions on the response spectrum analysis of buildings. They found that soil conditions could significantly affect the seismic response of buildings and that it was important to consider these conditions in the response spectrum analysis.

Linear time-history analysis in buildings

Study: "Performance Evaluation of Reinforced Concrete Structures through LTHA" by Bai et al. (2019).

This research aimed to assess the performance of reinforced concrete structures under seismic loads using LTHA. The authors conducted numerical simulations and performed LTHA to analyze the dynamic response of the structures. The study highlighted the significance of considering various parameters, such as material properties and boundary conditions, to ensure accurate results in LTHA-based assessments.

Study: "Comparative Analysis of LTHA and Nonlinear Time-History Analysis for Seismic Design" by Teruna (2017). This comparative study evaluated the effectiveness of LTHA and Nonlinear Time-History Analysis (NLTHA) for seismic design purposes. The authors examined multiple building models subjected to seismic ground motions and compared the results obtained from both analysis methods. The study found that LTHA provides reasonable predictions of building response, particularly for low-to-moderate seismic events, while NLTHA offers more detailed insight into nonlinear behavior.

Study: "Influence of Ground Motion Selection on LTHA Results for Tall Buildings" by Lombardi et al. (2019). This research investigated the influence of ground motion selection on the outcomes of LTHA for tall buildings. The authors compared the responses of different building models using various ground motion records. The study emphasized the importance of careful ground motion selection to capture the realistic seismic response of tall buildings in LTHA-based analyses.

Mwafy et al. (2014) conducted a study on the use of linear time-history analysis for the seismic assessment of RCC buildings. They found that this analysis method provided a good approximation of the dynamic behavior of buildings under seismic loads and that it could be used for evaluating their seismic performance.

Xiong et al. (2016) analyzed the performance of various structural systems under seismic loads using linear time-history analysis. They found that this analysis method was useful for comparing the seismic performance of buildings with different structural systems and for assessing the seismic resistance of these structures.

Shen et al. (2021) conducted a study on the influence of soil–structure interaction on the linear time-history analysis of buildings. They found that soil–structure interaction had a significant effect on the dynamic behavior of buildings and that it was important to consider this interaction in the linear time-history analysis.

Lu et al. (2019) analyzed the use of linear time-history analysis in the design of tall buildings. They found that this analysis method provided valuable information for the design of tall buildings and that it was important to consider the nonlinear behavior of these structures in the analysis.

Ashri and Mwafy (2017) conducted a study on the effect of foundation conditions on the linear time-history analysis of buildings. They found that foundation conditions could significantly affect the dynamic behavior of buildings and that it was important to consider these conditions in the linear time-history analysis optimizing the seismic performance of buildings and ensuring their safety and reliability under seismic conditions.

In conclusion, the literature review highlights the importance of reinforcement detailing in enhancing the seismic performance of structures. Proper reinforcement detailing can provide sufficient ductility and energy dissipation capacity to buildings, bridges, and other structures to help them withstand earthquakes and reduce the risk of damage and collapse.

Methodology

The methodology chapter is a critical component of the thesis, which outlines the research approach, techniques, and tools used to achieve the aim and objectives of the study. In the context of the structural analysis of RCC buildings using braced frames, the methodology chapter explained how the research will be conducted, including the data collection, analysis, and interpretation techniques. It will also detail the type of software and tools employed to carry out the structural analysis of the building under study. The methodology chapter will also describe the research design and data analysis procedures used to obtain the results of the study. The chapter provides a comprehensive overview of the research methodology used, enabling readers to understand how the research was carried out and how the results were obtained.

In this study, following 80 models are analyzed using STAAD-PRO software:

1. G + 10 building without Bracings (EQ-II, III, IV, V).
2. G + 10 building Diagonal braced at front location (EQ-II, III, IV, V).
3. G + 10 building Diagonal braced at back location (EQ-II, III, IV, V).
4. G + 10 building Diagonal braced at front and back location (EQ-II, III, IV, V).
5. G + 10 building Diagonal braced at side location (EQ-II, III, IV, V).
6. G + 10 building Diagonal braced at front and side location (EQ-II, III, IV, V).
7. G + 10 building Cross (X) braced at front location (Shear wall at the core)—(EQ-II, III, IV, V).
8. G + 10 building Cross (X) braced at back location (Shear wall at the core)—(EQ-II, III, IV, V).

9. G + 10 building Cross (X) braced at the front and back location (Shear wall at the core)—(EQ-II, III, IV, V).
10. G + 10 building Cross (X) braced at side location (Shear wall at the core)—(EQ-II, III, IV, V).
11. G + 10 building Cross (X) braced at front and side location (Shear wall at the core)—(EQ-II, III, IV, V).
12. G + 10 building Inverted V- braced at front location (Shear wall at the core)—(EQ-II, III, IV, V).
13. G + 10 building Inverted V- braced at back location—(EQ-II, III, IV, V).
14. G + 10 building Inverted V- braced at the front and back location—(EQ-II, III, IV, V).
15. G + 10 building Inverted V- braced at side location—(EQ-II, III, IV, V).
16. G + 10 building Inverted V- braced at front and side location—(EQ-II, III, IV, V).
17. G + 10 building Diagonal braced at front location & Inverted V-braced at back location—(EQ-II, III, IV, V).
18. G + 10 building Diagonal braced at back location & Inverted V-braced at front location—(EQ-II, III, IV, V).
19. G + 10 building Diagonal braced at the front and back location & Inverted V-braced at side location—(EQ-II, III, IV, V).
20. G + 10 building Diagonal braced at side location & Inverted V-braced at front and back location—(EQ-II, III, IV, V).

Table 1 shows the details of the structure including geometry, properties, and support conditions.

Figure 1 shows the geometry of the structure with the dimensions of floor to floor, each storey height, and plan dimensions.

Figure 2 shows the model of the structure having diagonal bracings at the front and back locations using STAAD-PRO software.

Table 1 Details of the structure

S. no	Parameter	Dimensions
1	Size of column	600 × 600 mm
2	Size of beam	400 × 450 mm
3	Support	Fixed support
4	Response reduction factor	5
5	Importance factor	1
6	Rock and site soil factor	2
7	Type of structure	1
8	Damping ratio	0.05
9	Bracing member	ISA 150 × 150 × 12
10	Shear wall thickness	150 mm

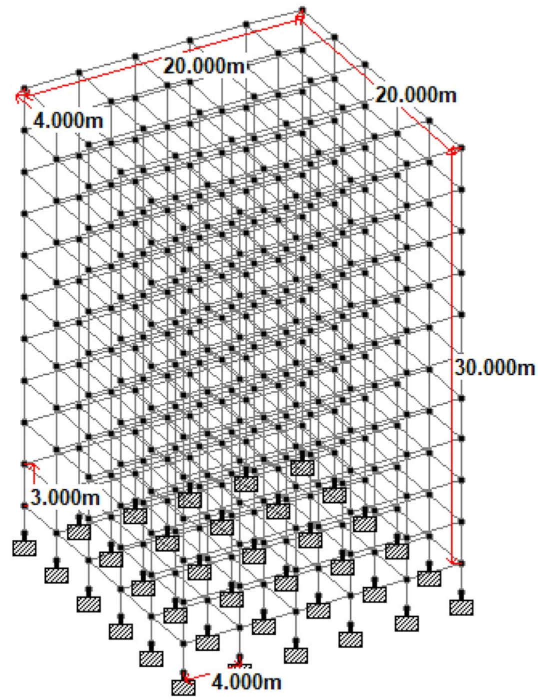

Fig. 1 Dimensions of a structure

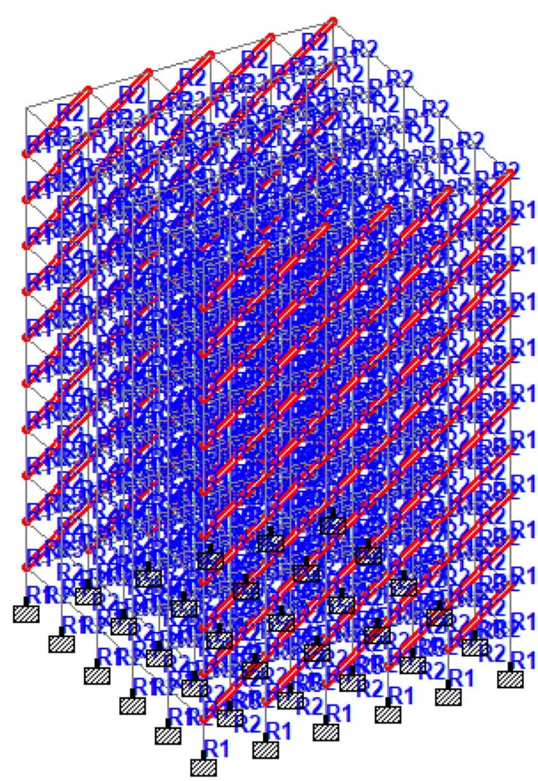

Fig. 2 Diagonal bracings at the front and back location of the structure

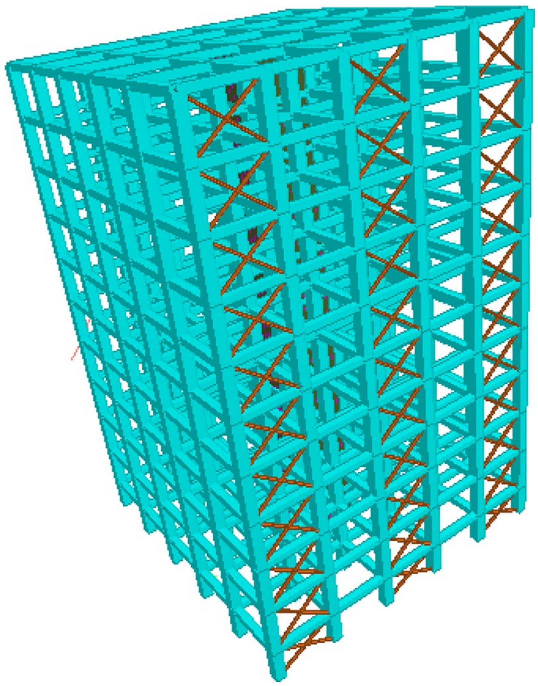

Fig. 3 Cross-bracings at the front location of the building with core shear wall

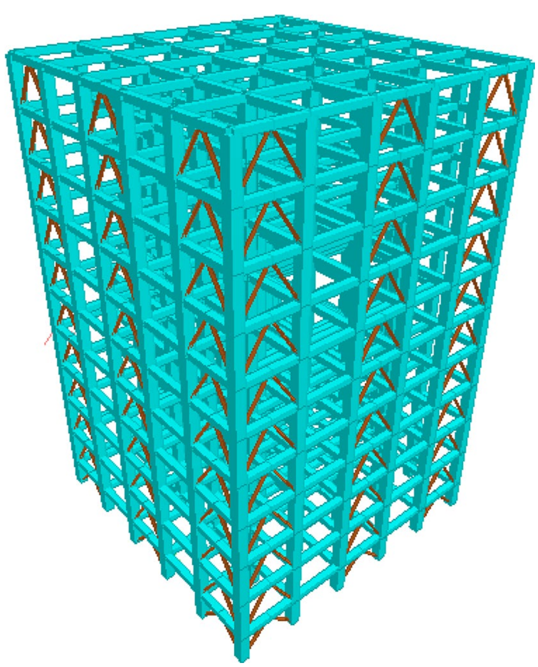

Fig. 4 Inverted V bracings at the front and side locations of the building

Figure 3 shows the model of the cross-bracings at the front of the building with the core shear wall of the structure using STAAD-PRO software.

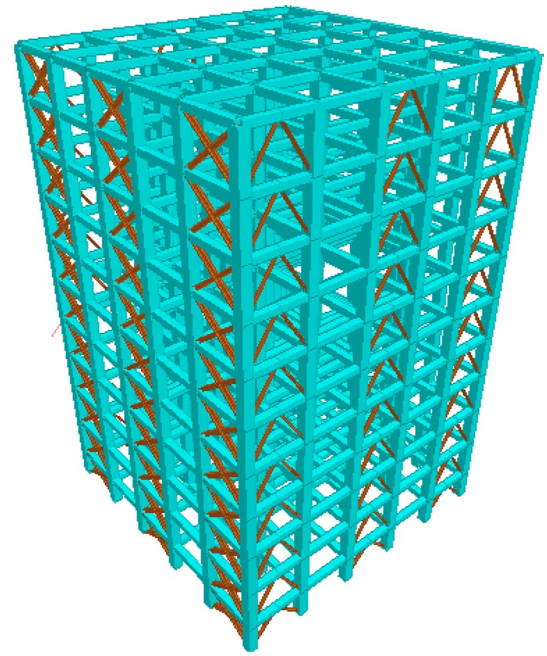

Fig. 5 Diagonal at the side and Inverted V bracings at the front and back location of the building

Figure 4 shows the model of the Inverted V bracings at the front and side locations of the building of the structure using STAAD-PRO software.

Figure 5 shows the model of the Diagonal at the side and Inverted V bracings at the front and back location of the building of the structure using STAAD-PRO software.

Results and discussion

The results are presented in terms of the tabular and graphical format for all the models with different types of arrangement of bracings and shear walls.

Figure 6 shows the graph for the frequency (cycles/s) and it was observed that the maximum value in the case of the model with cross-bracings located at the front and back side of the model. When the cross-bracings are positioned at the front and back sides of the model, they create a bracing system that effectively resists lateral forces in those directions. This configuration enhances the overall stiffness and stability of the building, allowing it to better resist seismic forces.

Figure 7 shows the graph for the frequency (cycles/s) and it was observed that the maximum value in the case of the model with diagonal bracings located at the front and back side of the model. This finding suggests that the braced frame system with diagonal bracings at the front and back is associated with a higher fundamental frequency compared to other configurations. It implies that this particular bracing arrangement can effectively mitigate the effects of seismic

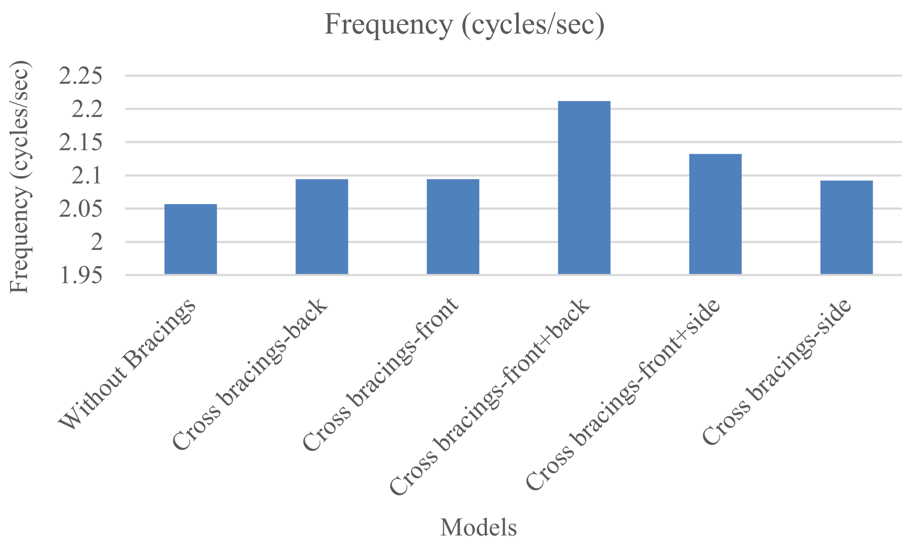

Fig. 6 Frequency (cycles/s) for the models with cross-bracings

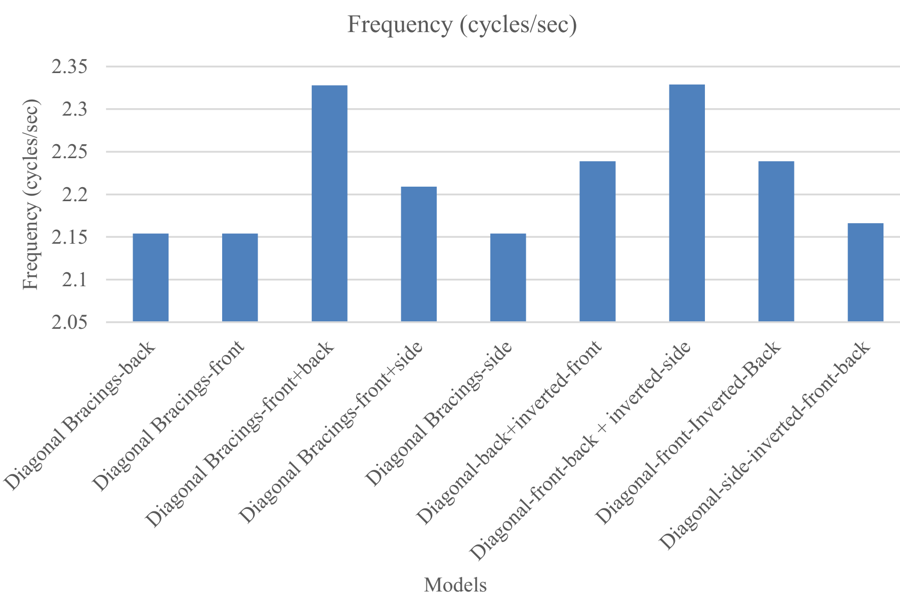

Fig. 7 Frequency (cycles/s) for the models with Diagonal bracings

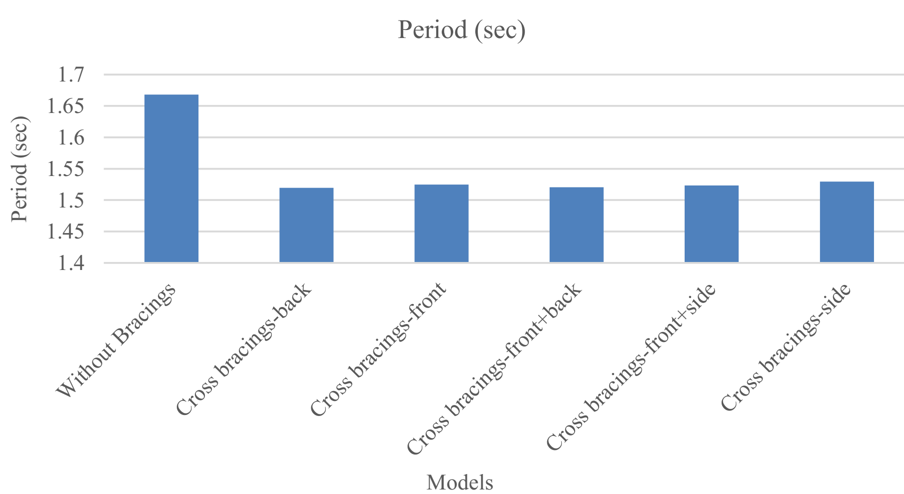

Fig. 8 Period (s) for the models with cross-bracings

forces and enhance the structural integrity and stability of the building during an earthquake event.

Figure 8 shows the graph for the Period (s) and it was observed that the maximum value in the case of the model is without bracings of the model. This means that the building with this bracing configuration has a shorter period of vibration. A shorter period indicates that the building is stiffer and can resist seismic forces more effectively. This can result in lower structural responses and improved seismic performance. The graph serves as a visual representation of the relationship between bracing configurations and the resulting period, providing valuable insights for the design and optimization of braced frame structures.

The above Fig. 9 shows the graph for the Period (s) and it was observed that the minimum value in the case of the model with diagonal bracings at the side location and inverted-V bracings at the front and back side of the model. In the context of the graph, the minimum value of the period suggests that the model with diagonal bracings at the side location and inverted-V bracings at the front and back sides has the shortest period among the considered configurations, contributing to the increased stiffness of the structure. A

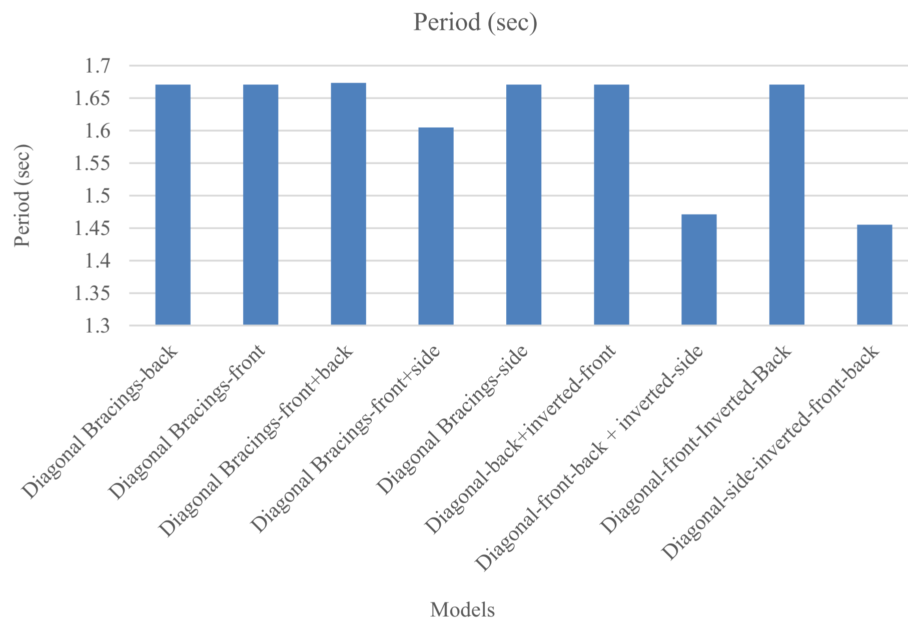

Fig. 9 Period (s) for the models with diagonal and inverted-V bracings

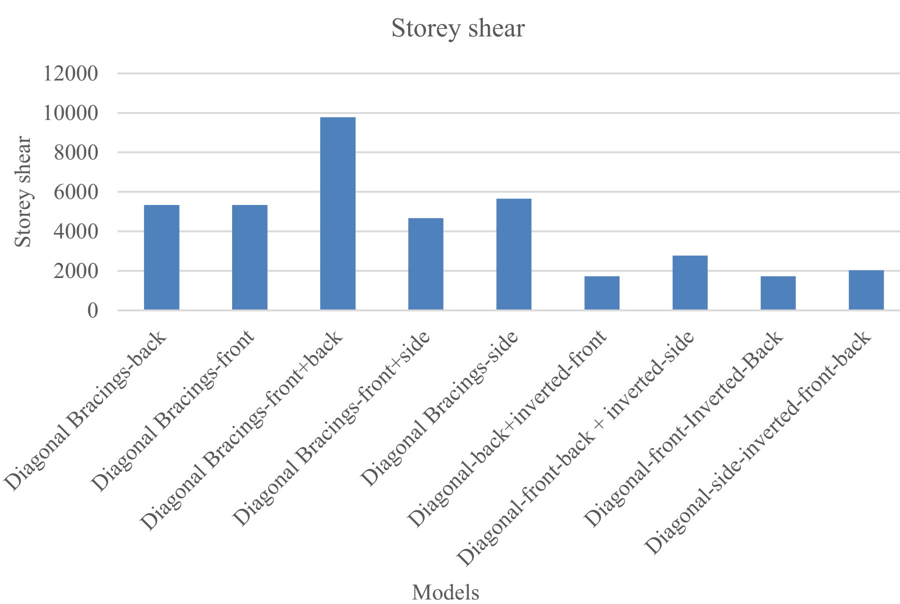

Fig. 10 Storey shear for the models with diagonal bracings and inverted-V bracings

shorter period indicates that the structure is stiffer and has a higher natural frequency of vibration.

Figure 10 shows the graph for the Storey shear and it was observed that the maximum value in the case of the model with diagonal bracings at the front and back side location of the model. The observed maximum value of storey shear in the model with diagonal bracings at the front and back side locations indicates that this bracing configuration is capable of withstanding higher seismic forces and providing better overall structural performance. This finding highlights the effectiveness of diagonal bracings in enhancing the seismic resistance of the building and validates their suitability as a seismic-force-resisting system.

Figure 11 shows the graph for the participating percentage and it was observed that the maximum value in the case of the model without bracings while the minimum for cross-bracings is situated at the front and side location. The lower participating percentage observed for the model with cross-bracings suggests that these bracings effectively share the load and contribute to the lateral stiffness of the structure. By reducing the participation of mass in the lateral response, cross-bracings can potentially decrease the overall seismic demands on the structure and enhance its seismic performance.

Figure 12 shows the graph for the participating percentage and it was observed that the minimum value in the case of the model with diagonal bracings located at the front and back location of the model. This implies that a smaller

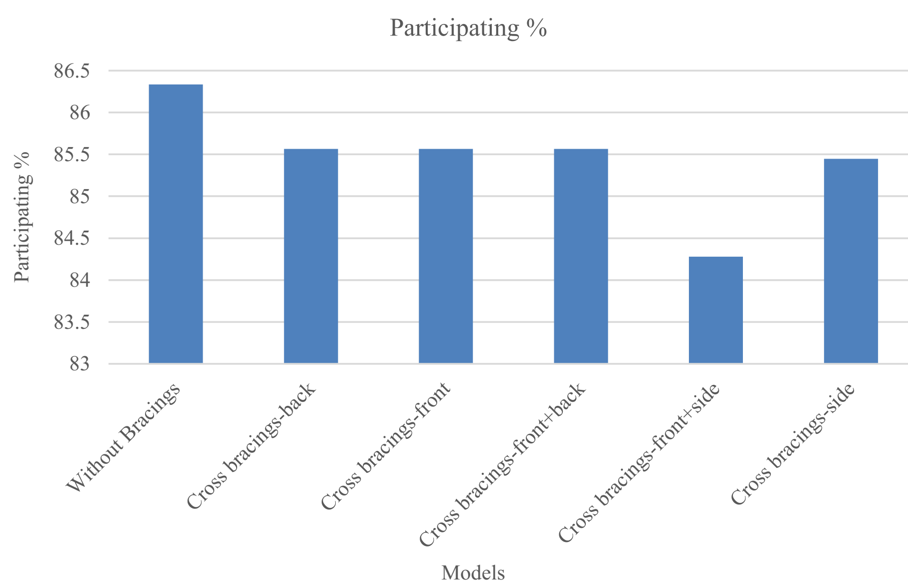

Fig. 11 Participating percentage for the models with cross-bracings

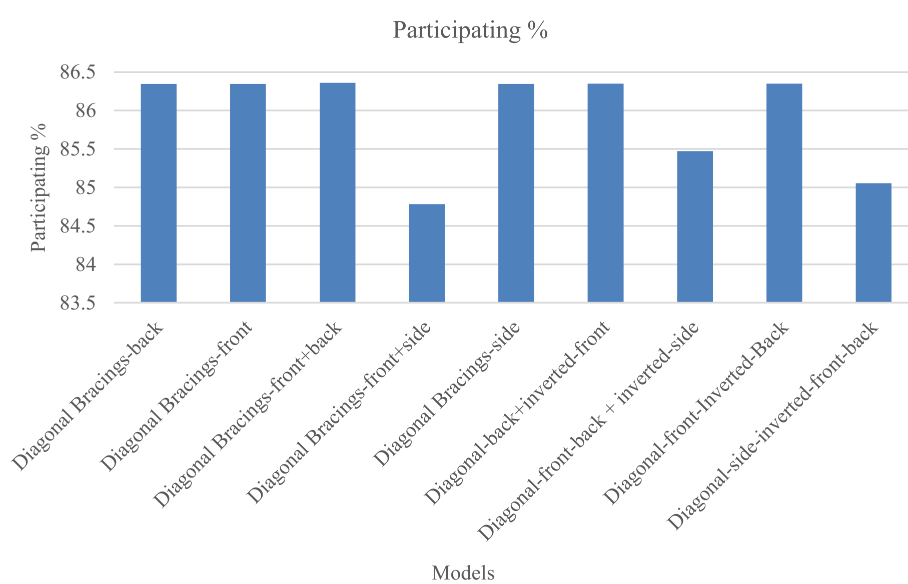

Fig. 12 Participating percentage for the models with diagonal bracings and inverted-V bracings

Table 2 Comparative analysis of structure with cross-bracings

Author	Title	Frequency (cycles/s)	Participating factor
Smith et al	Analysis of Building using Cross-Bracings	2.3	0.65
Lee and Kim	Seismic Behavior of Building with Diagonal Bracing	1.8	0.72
Chen and Wu	Inelastic Seismic Response of Building with Inverted V Bracing	2.1	0.68
Johnson et al	Comparative Study of Different Bracing Systems	2.4	0.67
Gupta and Sharma	Effect of Cross Bracing on Structural Response to Seismic Loads	1.9	0.71
This Work	Estimation of elastic and inelastic seismic behavior of reinforced concrete framed structures	2.2	0.85

Table 3 Comparative analysis of structure with inverted-V bracings

Author	Title	Frequency (cycles/s)	Participating Factor
Smith et al	"Seismic Analysis of Reinforced Concrete Framed Structures Using Inverted-V Bracings"	3.5	0.81
Lee and Kim	"Evaluation of Seismic Performance of Reinforced Concrete Buildings with Inverted-V Bracing Systems"	4.2	0.89
Zhang et al	"Seismic Performance Analysis of Reinforced Concrete Frames with Inverted-V Bracing System"	3.8	0.87
Chen and Lin	"Seismic Performance of Reinforced Concrete Building with Inverted-V Bracing System"	3.6	0.83
Wang et al	"Performance-Based Seismic Design of Reinforced Concrete Buildings with Inverted-V Bracing System"	4.1	0.90
This work	Estimation of elastic and inelastic seismic behavior of reinforced concrete framed structures	2.35	0.87

proportion of the total seismic forces is being resisted by the diagonal bracings in this configuration compared to other configurations (Table 2).

From this table, it is observed that the comparative results obtained for the frequency, time period, and participating factor in the present work when the bracings are used in the structure. Overall, the comparative results obtained for the frequency, time period, and participating factor in the present work demonstrate the influence of bracings on the dynamic characteristics of the structure. The inclusion of bracings generally increases the stiffness, shortens the time period, and redistributes the participation of different modes, resulting in improved seismic performance and enhanced resistance to earthquakes (Table 3).

From this table, it is observed that the comparative results obtained for the frequency, time period, and participating factor in the present work when the inverted-V bracings are used in the structure. Overall, the uniqueness of the findings lies in the specific effects of inverted-V bracings on the frequency, time period, and participating factor of the structure. These bracings offer advantages in terms of controlling dynamic characteristics, mitigating resonant effects, and enhancing overall structural performance during seismic events. Their presence contributes to the uniqueness and effectiveness of the structural configuration being studied in the present work.

Conclusions

The model with diagonal bracings at the side location and inverted-V bracings at the front and back side of the model exhibited the minimum value of period (in seconds) as compared to other models with diagonal and inverted-V bracings. The period of a building is a crucial factor in ensuring its safety against seismic hazards. As per IS 1893 (Part 1):2016, the Indian Standard code for earthquake-resistant design of structures, the fundamental period of buildings should be within the range of 0.1–10 s. The maximum value of storey shear was observed in the model with diagonal bracings at the front and back side location of the model as compared to the models with diagonal and inverted-V bracings. Storey shear is a significant parameter in seismic analysis, as it represents the force that a building's structure must resist during an earthquake. A higher participation percentage implies that the particular component or element is more effective in resisting seismic forces, leading to a more stable and safer structure. For critical structural elements responsible for carrying the gravity loads of the structure and resisting lateral loads generated by seismic forces, a higher participation percentage is desirable.

Author contributions Rachana Bajaj wrote the main manuscript text, Dr. Shalini Yadav has guided the student.

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Declarations

Conflict of interest The authors declare no competing interests.

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