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Seismic Performance of High Rise Flat Slab Structure with Reinforced Concrete Outriggers in Seismically Active Regions: A Case Study

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This study investigates the seismic performance of a 20-storey reinforced concrete office building with dimensions of 30m x 48.75m and a storey height of 3.40m. The building's lateral stability is ensured by shear walls, outriggers, and perimeter belt trusses on the 20th floor. Gravity loads are transferred through a flat slab system supported by perimeter edge beams, with the entire structure resting on a pile-supported mat foundation. The structural elements are cast in-situ using C40 concrete. Two cases were analyzed: Case 1 without outriggers and Case 2 with reinforced concrete outriggers. Finite Element (FE) software ETABS was used for global analysis, adhering to the National Structural Code of the Philippines (NSCP) 2015. The study comprises three phases: development and analysis of the building model, determination of seismic response, and evaluation

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of seismic response. Results indicate that the inclusion of outriggers significantly improves the building's seismic response, reducing the fundamental period from 3.322s (Case 1) to 2.929s (Case 2). The study concludes that reinforced concrete outriggers are an effective and practical solution for enhancing the seismic performance of high-rise buildings.

Keywords: Finite element analysis; flat slab system; high-rise structures; reinforced concrete outriggers; seismic performance.

1. INTRODUCTION

In the face of economic development of countries together with countless advancement in technology around the world, it is undeniably apparent that this progress always carries with them the hurdle brought by fast growing population around the world. This social issue results to limited and diminishing available land areas to accommodate increasing human population [1]. The circumstance makes high-rise building not just a symbol of luxury and affluence but overtime, becomes a necessity.

Construction of high-rise buildings is prompted to address problems arising due to dropping amount of unoccupied land spaces. Vertical expansions have become one of the solutions to the problem faced by densely populated urbanized areas and cities [2]. Furthermore, according to Gonzaga [3] the occurrence of natural calamities such as earthquake, typhoon, and many others, may cause damage and different effects to the structures.

The seismic performance of high-rise flat slab structures with reinforced concrete outriggers in seismically active regions is a critical area of study, particularly in urban environments where such buildings are prevalent. This case study investigates and elaborates on the differences in seismic response between high-rise buildings with and without reinforced concrete outriggers, both featuring flat slab floor systems.

Flat slabs are commonly adopted in buildings that require high ceiling floors and flexible column layouts, which enhance space occupancy, reduce total building height, and allow for shorter construction times and less formwork [4]. These characteristics make flat slab systems advantageous for residential buildings, car parks, and other high-rise structures with public spaces [5,6]. However, the inherent low stiffness of flat slabs makes buildings more vulnerable to lateral loads, resulting in extreme deformations during seismic events [7].

To mitigate these excessive deformations, the incorporation of outriggers in high-rise buildings is introduced in this case study. The study evaluates the seismic response of a 20-storey flat slab building with a reinforced concrete outrigger positioned on the 20th floor. The response indicators considered in this study include maximum displacement, storey drift, storey shear, and modal time period [8,9].

The supreme and integral part of the design of high-rise building is for them to bear up against lateral forces that most likely to act on the structure during seismic events (Minimol J.S., 2023).

The outrigger system has been proven through several studies to be one of the lateral resisting systems that can be practically used to minimize seismic induced lateral loads [10]. According to Arvind JS (2023) and Ho G [11], distribution of lateral loads within central core which can be shear walls and the permitter walls or columns, thus, minimizing the stresses, lateral deflections and overturning moment of structural components.

Subsequently, this study intends to evaluate the effects of reinforced concrete outriggers to high-rise buildings with flat floor slab system and comparing it to completely similar structure without outriggers.

Together with the increasing demand to construct high-rise buildings is also the increase of risk in terms of safety to public given the fact the majority of the Philippine archipelago is within seismic zone 4 where earthquakes are more likely to occur. Though magnitude and occurrence of large seismic events are unpredictable, risks and hazards present on high-rise building can be significantly reduced with proper structural design and analysis.

According to Herath N. et al. (2013), when the building expands vertically, structure's stiffness increases substantially. Excessive deformations caused by seismic loads that may later progress to failure and collapse of the buildings can be counteracted by integrating lateral resisting frames such as outriggers in the building (Alanazi, 2019; Po Seng Kian, et al, [12]). The outrigger system in towering buildings is an implicit method to improve the building's resistance against seismic loads (Arvind JS, 2023).

This study focused on a 20-storey reinforced concrete office building with a typical plan dimension of 30 meters (m) x 48.75m and a typical storey height of 3.40 m. The lateral stability of the structure is provided by shear walls in conjunction with outriggers and perimeter belt trusses on the 20th floor. Perimeter columns are also provided and will be engaged in the frame action by outriggers. The gravity loads are transmitted into the vertical elements through a flat slab system supported by perimeter edge beams, and the entire building sits on a pile-supported mat foundation. The structural walls, slabs, columns, and beam elements are cast in-situ C40 concrete. In the process of this investigation, two cases were considered in this study, namely:

Case 1 - Building without outrigger;
Case 2 - Building with reinforced concrete outriggers.

The global analysis of the structure was performed using Finite Element (FE) software Extended Three-dimensional Analysis of Building Structures (ETABS), and separate models were developed for each case. The analysis and design conform with the provisions of the National Structural Code of the Philippines (NSCP) 2015.

For case 2, the outriggers are located on the 20th floor. The response of the building under seismic loading was evaluated and compared to determine the efficiency of the structural system with outriggers. The results of analysis from the three-dimensional (3D) FE model, particularly the modal period and frequency, were checked using hand calculations.

2. RELATED LITERATURE

The seismic performance of high-rise flat slab structures with reinforced concrete outriggers in seismically active regions has been a subject of extensive research. Gupta and Gupta [13] conducted a comprehensive seismic analysis of reinforced concrete (RC) flat slab buildings using ETABS software, focusing on various structural configurations and their seismic performance. They highlighted the importance of structural elements like drop panels, column heads, and area beams in enhancing seismic resilience. Similarly, Doğan and Erkan [14] evaluated the nonlinear seismic responses of high-rise RC buildings, emphasizing the significance of soil-structure interactions (SSI) in improving structural integrity and delaying plastic hinge formation. Their study demonstrated that considering SSI in the design stage can significantly enhance the seismic performance of buildings.

Chatzidaki et al. [15] discussed the architectural flexibility and efficient load distribution of RC flat slab buildings, noting that their performance under seismic loads requires careful design and detailing to prevent catastrophic failures. Bruschi and Quaglini [16] also emphasized the need for comprehensive guidelines, such as IS 456:2000 for design and IS 13920:2016 for ductile detailing, to enhance the seismic performance of RC structures. Patil et al. [17] and Sharma and Trivedi [18] underscored the critical role of structural integrity and seismic resilience in ensuring safety during earthquakes.

Further, Polat and Erkan [19] highlighted the impact of different foundation types and structural plans on the seismic responses of high-rise RC buildings. Their findings indicated that base shear forces and roof displacements vary significantly with different SSI situations, demonstrating the importance of considering these factors in seismic design. Additionally, the study by Kaveh et al. [20] provided valuable insights into the seismic performance of RC flat slab buildings, reinforcing the need for robust design and detailing practices.

In the definition of high-rise building in terms of its height, Reeves [21] states that according to Section 202 of the 2015 International Building Code, a building is considered a high-rise when the highest occupied floor is more than 75 feet above its lowest level of fire department vehicle access. High-rise buildings intently having massive number of structural components and elements contrasting low-rise structures is as well complicating the edifice by the demand to have high structural stability for safety and design requirements (Imad Shakir et al. (2021).

Tailor J. [22] states that the structural systems are like the skeletal system comprising the bones of the human body, which primarily combines various elements to serve a common purpose. The interaction of each elements connected to each other to form a complex structure allows the whole assembly to counteract different loads acting on it. Furthermore, He also stated, "A building can also be understood as a physical embodiment of several systems and subsystems integrated forming building as a whole." According to Gore and Mhatre [23], the different high-rise building structural systems which includes braced frame, rigid frame, wall-frame, shear wall, core and outrigger, infilled frame, flat plate, flat slab, tube, coupled wall, and hybrid structural systems above systems are divided into interior and exterior systems. Their studies compared tables to determine which system provides the higher number of floors with structurally stable configuration with outrigger proving to be more prevalent than other systems.

According to Arvind JS (2023), distribution of lateral loads within central core which can be shear walls and the permitter walls or columns, thus, minimizing the stresses, lateral deflections and overturning moment of structural components. Using ETABS Software, evaluation of the dynamic analysis of outrigger braced systems incorporated to high-rise steel building was conducted by Sathyamurthy K. et al. [24] with seven different steel building models. The models had different versions of bracings. They analyzed shear coming at the base, drift of the storeys, displacement of the storeys, and time period. Kavyashree, Patil, and Rao [25] presented a concise history of where the outrigger system concept was derived. It was introduced for rollover stabilization of canoes, and its concept was carried over to other systems that require roll stability, as a result the concept was then further utilized for tall, slender structural system.

The literature consistently emphasizes the importance of structural elements, soil-structure interactions, and comprehensive design guidelines in enhancing the seismic performance of high-rise flat slab structures with reinforced concrete outriggers in seismically active regions. These studies provide a solid foundation for designing safer, more resilient buildings capable of withstanding seismic forces.

3. METHODOLOGY

The study is divided into three (3) phases. Phase 1 comprises the development and analysis of the building model using 3D FE analysis, Phase 2 comprises the determination of seismic response, and Phase 3 includes the evaluation of seismic response. Evaluation of the effects on the seismic response of outriggers to the high-rise buildings can be carried out using analytical and scientific method. To achieve the real and close to actual interaction of outriggers, shear wall, columns, and flat slabs as diaphragms, configuration of the structure to be used in the study was established, the specific loading and other design parameters correspond to the building properties including the site location were classified and characterized. The FE software to be used was also identified.

3.1 Phase 1: Develop and Analyze the Building Model

At this stage, the establishment of building layout, size of structural elements, and finding of appropriate design parameters was carried out. The properties of the building in the study were defined in terms of geometry (plan and vertical), type and strength of materials, load magnitudes, and validity of structural element sizes based on the minimum code requirements needed to develop a 3D FE model using Computer and Structures, Inc. ETABS. The models were used to perform the analysis and design of the structure.

3.1.1 Establish the plan and elevation configuration of a 20-storey building

The building considered in the study is a 20-storey office building 30 m wide and 48.75 m long with typical floor plan and identical storey height of 3.4 m. The structure comprised three basement levels and 20 floors above ground, as shown in Figs. 1 and 2. The entire building sits on a piled foundation.

The building consists three (3) spans of 6 meters each along North-South direction, and five (5) spans of 8.6 meters each along East-West direction. The lateral stability of the building is provided by shear wall of thickness ranging from 300 millimeters (mm) to 400 mm. The typical column sections are 1.0x1.0m, typical floor beam sections are 400mm x 700 mm, and flat slab thickness is 300 mm [26-28].

3.1.2 Determine the design parameters

The design parameters used in this study were based on the provisions recommended in the

NSCP 2015. The researchers defined the properties of the materials used in the study such as compressive strength $(f'c)$ of concrete equal to 45 Megapascals (MPa), unit weight of concrete is taken as 23.45 kN/m3, concrete elastic modulus taken as $4700\sqrt{f'c}$, yield strength of reinforcing steel taken as 414 MPa, and unit weight of reinforcing steel taken as 77 kN/m3, among others. The parameters also include excitations such as dead load, live loads, wind load and earthquake load. The dead load is associated to the unit weight and size of permanent elements whether structural and non-structural, and live load was defined based on the anticipated load from the occupants taken as 3.0 kPa for this study. Wind load parameters vary from one place to another based on the wind pressure map of the NSCP. On the other hand, site-specific seismic parameters were determined to correspond to the proposed site location as shown in Fig. 4 The site location is at Catubig northern Samar, around 50 kilometers away from nearest active fault line. It is within seismic zone 4 with soil profile type SC, seismic source type A, and response reduction factor of 8.5 corresponds to shear wall structural system.

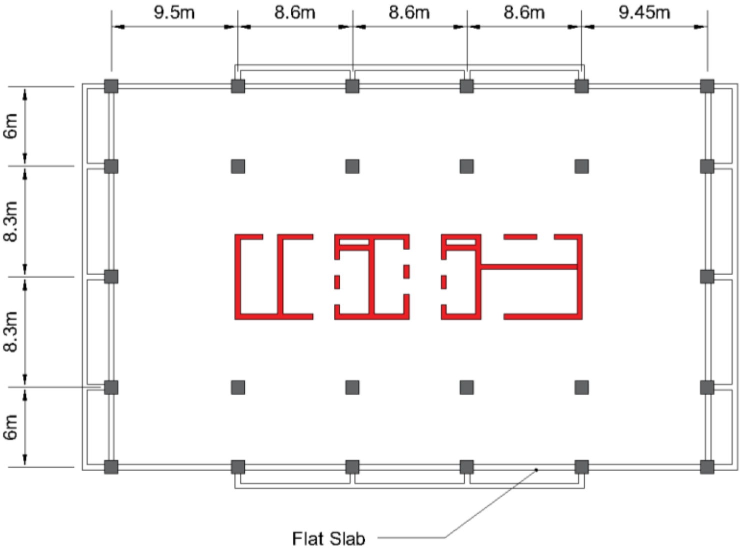

Fig. 1. Typical floor plan

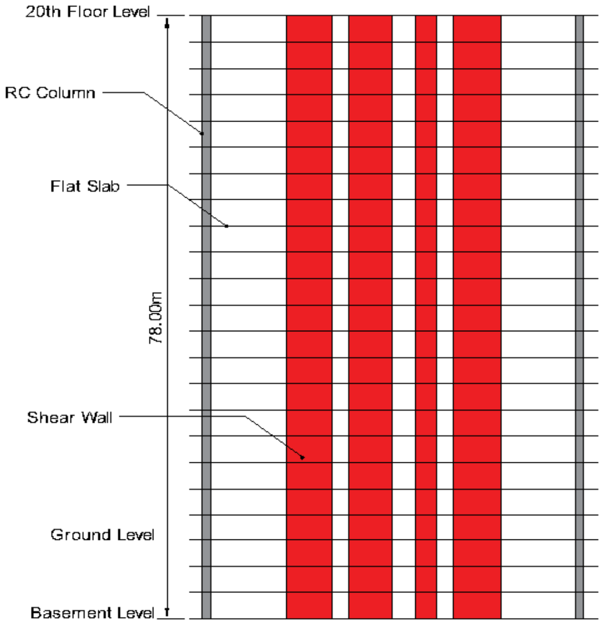

Fig. 2. Typical elevation

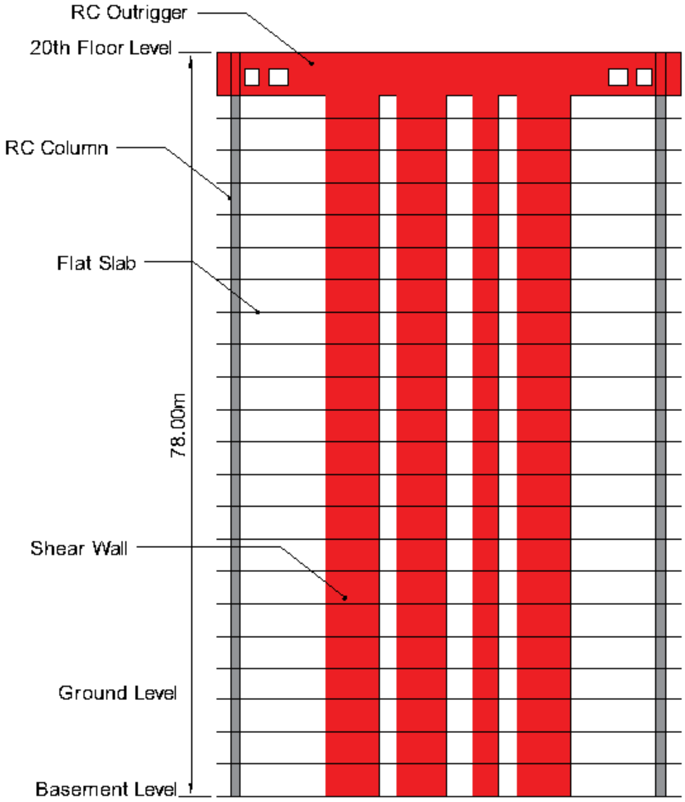

Fig. 3. Proposed location and configuration of reinforced concrete outriggers

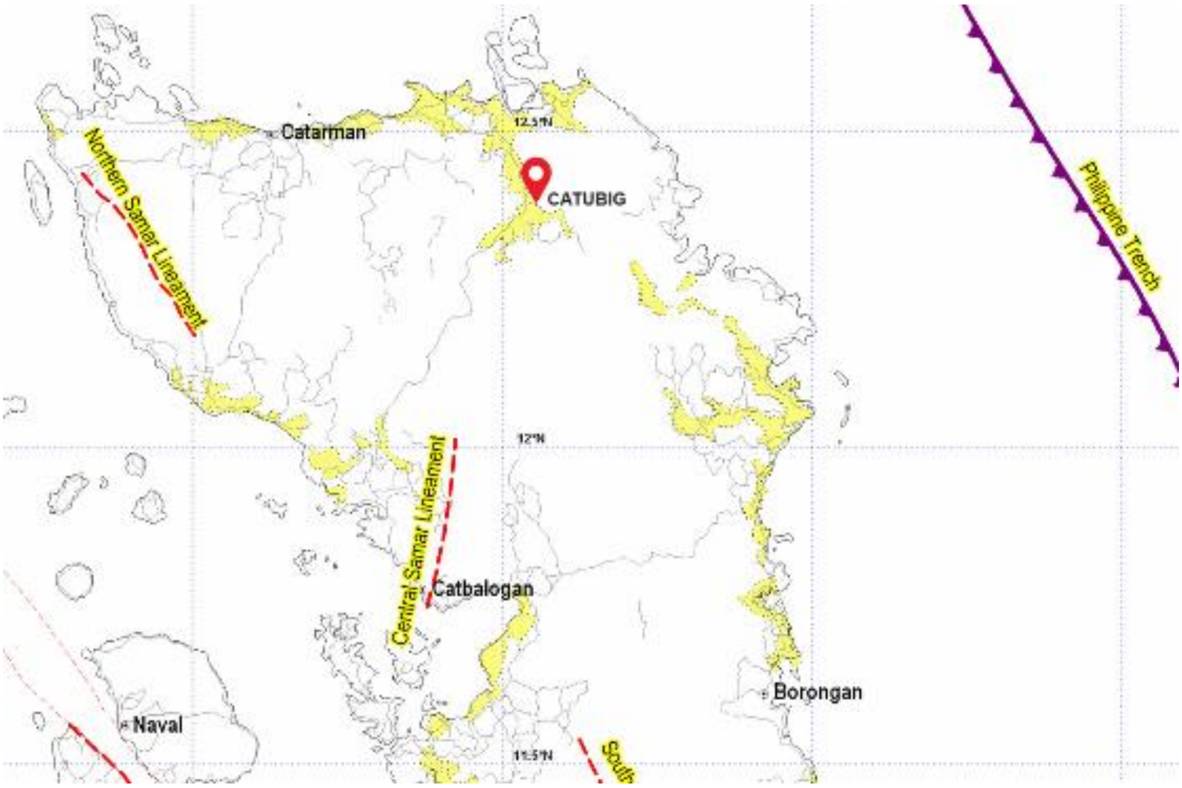

Fig. 4. Proposed site location

3.1.3 Create thwo (2) separate building models for case 1, and case 2using 3D FE software ETABS

The three-dimensional building models were formed using a commercial finite element analysis software named ETABS. Two (2) separate models were created in conformance with the provisions of the NSCP and Uniform Building Code (UBC)1997 as shown in Fig. 5. The models incorporate the building geometry, element sizes, and design parameters defined in steps 4.1 and 4.2. The first model comprises a shear wall system without an outrigger. Walls and flat slabs were modeled as shell elements, while columns and beams were modeled as frame elements. The flat slab was considered to act as a rigid diaphragm. The second model is composed of shear wall system with reinforced concrete outriggers on the 20th floor. Both models are identical except with the provision of outriggers on the second model.

The combined actions of loads were defined in the FE models considering the recommendations for Load Factor Resistance Design (LFRD) and serviceability limit states in the NSCP. Dead and superimposed dead loads, live loads including the earthquake parameters used in this study are enumerated on the tables presented below.

The effects of the cracked section were accounted for in the model. Walls, columns, beams and slabs were considered cracked in-service state based on the provisions of the American Concrete Institute (ACI) 318 and UBC 97. The factors used by the researchers to account for the effective section stiffness of the structural elements were derived from the crack modifiers for the Ultimate Limit State (ULS) divided by (1 + Bd). Table 5 shows the ULS crack modifiers and their corresponding service level (SLS) modifiers.

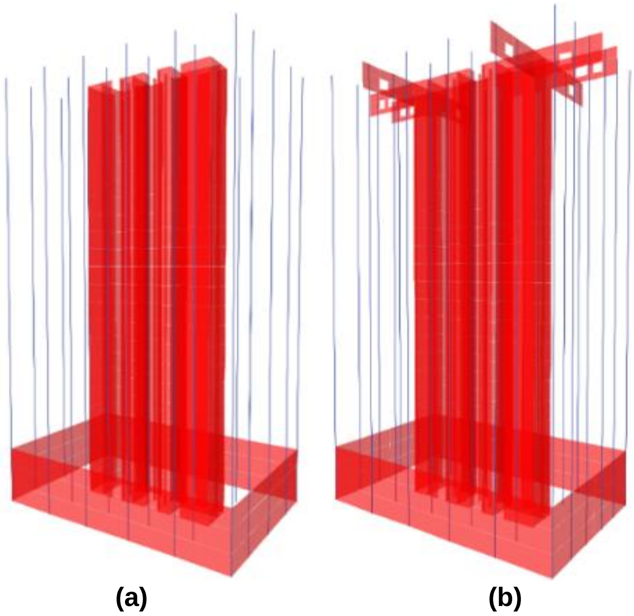
(a) (b)

Fig. 5. (a) ETABS model for case 1; (b) ETABS model for case 2

Table 1. Dead and superimposed dead loads

Materials/ Load Type	Weight
Reinforced Concrete	24.0 kN/m^3
SDL	7.00 kN/m^2

Table 2. Live loads

Location/ Area	Load
All areas	3.00 kN/m^2

Table 3. Earthquake parameters

Parameter	Value
Soil Profile Type	S_C
Seismic Zone	4
Seismic Source Type	A
Distance from fault line	8.90 km
Importance Factor	1.0
Over strength Factor	8.5

Table 4. Earthquake (EQ) load combination

ULS	SLS
1.41D + 0.5L + 1.0EQ	1.11D + 0.75L + 0.54EQ
0.99D + 0.5L - 1.0EQ	0.89D + 0.75L - 0.54EQ
1.11D + 0.5L + 1.0EQ	0.75D + 0.71EQ
0.69D + 0.5L - 1.0EQ	0.45D - 0.71EQ
	1.15D + 1.0L + 0.71EQ
	0.85D + 1.0L - 0.71EQ

Table 5. Crack section modifier

Structural Element	ULS Crack Modifier	SLS crack modifier
Walls	0.35Ig	0.50Ig
Beams	0.35Ig	0.50Ig
Columns	0.70Ig	1.00Ig
Slabs	0.20Ig	0.35Ig

Note: Ig is the gross moment of inertia of the section

3.1.4 Perform final check of 3D FE model in terms of element connectivity, meshing, loadings, and design parameters

After the 3D FE models were created, a sensibility check and model verification were performed. The design input was compared manually against the design parameters defined in step 2. Further validations were carried out to check element connectivity, meshing and loadings. The magnitude of loads was cross-checked to verify if the loads applied in the model are in agreement with the loading plans. Manual column load takedown was also excuted to check correctness in applied loads.

3.1.5 Finalize the 3D FE model and perform analysis

When the 3D FE models were fully checked, three separate models were saved as a new model for frequency analysis and earthquake drift.

3.1.6 Examine seismic responses against code permissible limits

After performing the analysis and design using ETABS, the results were examined to scrutinize the building behavior for irregularities relative to the normal response, and if found unacceptable, modification of the model will be done to normalize the results. This step has no direct implications for other steps. This serves as a quality check and assurance on the sensibility of the final FE model as well as the results prior to extracting the results data for each response indicator which were done in Phase 2. The mass participating ratio was checked and reached 90% with 18 modes. The maximum earthquake-induced drift was briefly checked here not to exceed 0.020 of the floor heights.

3.2 Phase 2: Determination of Seismic Response

This phase includes extraction, consolidation, and classification of building responses such as displacement, storey shear and modal time period generated by the 3D FE model. Displacement was taken from the most critical location in the model.

3.2.1 Extraction of maximum inelastic displacement of building, storey shear, and modal time period from analyzed 3D FE models

The calculated elastic displacement, Δ_S, was extracted from the model, then the maximum inelastic response displacement, Δ_M, was estimated using the equation recommended by the NSCP 2015 and UBC 1997 as shown in equation 2a.

$$\Delta_M = 0.7\ R\ \Delta_S \qquad (2a)$$

$\Delta_S = elastic\ displacement\ (mm);$
$R = Overstrength\ Factor$

The storey shear and modal time period were extracted from the model, and then presented in both graphical (see Figs. 6 to 7,) and tabular (see Tables 6 to 10).

3.2.2 Classification of data for seismic responses between the three cases

The extracted data were sorted out per seismic response for each case separately. The data were consolidated, classified, and presented in a single table for each seismic response for a clear and articulate comparison of all three models. Then, the summarized data were evaluated and checked quickly as to the sensibility of results following the expected behavior of the building. If the data demonstrate an unusual pattern, a subsequent check on the 3D FE model was performed.

3.3 Phase 3: Evaluation of Seismic Response

Phase 3 is the last stage of the methodology. It consists of 2 steps that explain the evaluation and assessment of seismic responses of the building with and without outriggers. Prior to performing this work, it requires a thoroughly checked 3D FE model as well as a validated result in order to come up with a more rational finding.

3.3.1 Comparison of seismic responses of each model in terms of total displacement, inter-storey drift, storey shear, and natural period

After consolidation and classification of data for each seismic response indicator, a detailed comparison was performed between the building without outriggers and with outriggers in terms of maximum inelastic displacement, storey shear, and natural period. The maximum inelastic displacement of the building measures the performance of the building in terms of the magnitude of sway. Greater displacement exhibits flexibility of the lateral-resisting system. Further, excessive displacement pertains to deformation that exceeds the permissible limit in the code i.e. 0.020~0.020 times storey height. If the building displacement exceeds the limiting value, it may affect the strength of elements that could affect the performance of the building under seismic load and compromised life safety. Excessive displacement may also incur damage to the adjacent building, hence this must be designed and controlled properly. The model with greater displacement demonstrates poor seismic response. Moreover, the seismic response was also measured based on the natural period and frequency of the building, longer period denotes a less stiff lateral system. A longer period reflects low horizontal frequency. The model with a longer period reveals poor seismic response.

3.3.2 Assessment of the seismic responses and evaluation of outriggers efficiency

This is the last step of the methodology which provides an answer to the main objective of the study. The consolidated and classified seismic responses in the previous steps were interpreted and assessed. In a specific manner, the overall implications of introducing outriggers in the lateral-resisting system, whether efficient or adverse, are discussed here in detail. Further, conclusions, as well as recommendations, are made here on the merit of outriggers in high-rise buildings using shear wall and flat slab systems.

4. RESULTS AND DISCUSSION

The modal time period for each case was determined using 3D FE software ETABS. Table 6 and Fig. 6 show the values and graph of the calculated period in seconds for all two cases. The graph shows that Case 1 or building without outrigger has the longest fundamental period (T = 3.322 s) while Case 2 or building with reinforced concrete outriggers yields the shortest period (T = 2.929 s). This is in good agreement with the results presented by Alhaddad et al. (2020), which show that as the number of outriggers increases, the period of the structure decreases. The decrease in period is equivalent to a rise in base shear as period (T), and shear (V) are inversely proportional.

Figs. 7 and 8 show that modes 1 and 3 are governed by the translation (Ux, Uy) along the principal axis, while mode 2 is governed by rotational translation (Rz). This means that the system has greater lateral stiffness along X-axis compared to Y-axis.

Table 6. Modal time period

Mode	Period (s)	
	Case 1	Case 2
1	3.322	2.929
2	2.643	2.754
3	1.789	1.711
4	0.768	0.752
5	0.696	0.627
6	0.467	0.456
7	0.387	0.375
8	0.289	0.279
9	0.241	0.234
10	0.226	0.23
11	0.17	0.168
12	0.169	0.166
13	0.143	0.147
14	0.129	0.126
15	0.117	0.118

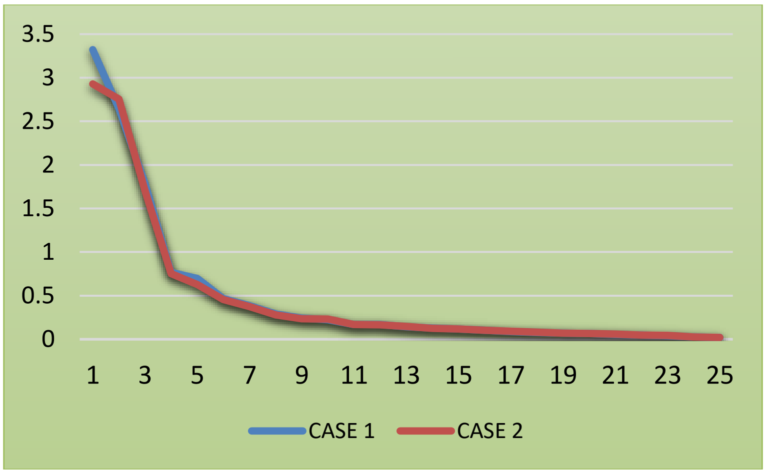

Fig. 6. Modal Period for all Cases

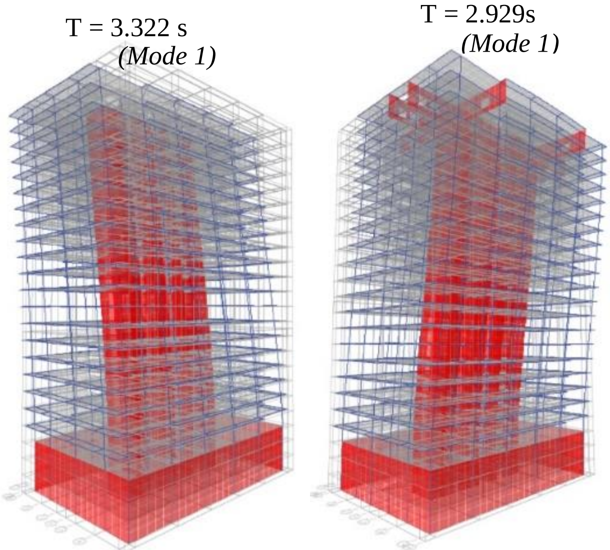

Fig. 7. Mode Shape along Y-direction for all Cases

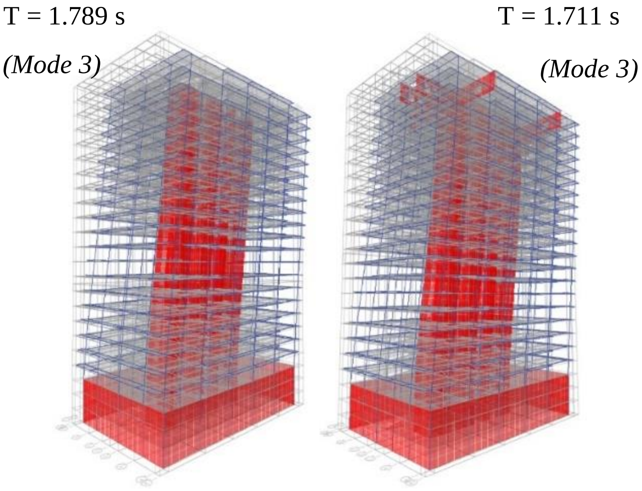

Fig. 8. Mode Shape along X-direction for all Cases

Table 7 shows the storey shear of both cases 1 and 2. The tabulated result show an increase of shear for case 2. This means that the provision of outriggers affects the distribution of base shear. As mentioned earlier, the decrease in period is equivalent to a rise in base shear as period (T), and shear (V) are inversely proportional and that is what happened as we recorded the significant increase in shear. These manifest that outriggers influenced the lateral stiffness of floors, and thus reduce the lateral displacement of the building.

Fig. 9 illustrates the inter-story drift along X and Y directions for all two cases and demonstrates a consistent pattern. At the topmost floor level, the story drift dropped by 40.0% from Case 1 to Case 2. Also, Fig. 10 shows the maximum inelastic response displacement for all cases with a recorded decrease of 4% and 6% from Case 1 and 2 along X and Y directions, respectively.

Table 7. Storey shear for all cases along X-direction

Storey	Elevation	Storey Shear Along X-Direction (kN)	
		Case 1	**Case 2**
20/F	78	3012	3034
10/F	44.0	15749	18503
G/F	10.0	22443	25520
B3	0.0	3012	3034

Table 8. Storey Shear for all cases along Y-direction

Storey	Elevation	Storey Shear Along Y-Direction (kN)	
		Case 1	**Case 2**
20/F	78	2359	2414
10/F	44.0	7075	9652
G/F	10.0	13335	15673
B3	0.0	2359	2414

Table 9. Inter-storey drift for all cases along X-direction

Storey	Elevation	Storey Drift Along X-Direction (mm)	
		Case 1	**Case 2**
20/F	78	0.737	0.299
10/F	44.0	0.964	1.009
G/F	10.0	0.133	0.178
B3	0.0	0.00	0.00

Table 10. Inter-storey drift for all cases along Y-direction

Storey	Elevation	Storey Drift Along Y-Direction (mm)	
		Case 1	Case 2
20/F	95	1.52	0.797
10/F	44	1.475	1.57
G/F	10	0.159	0.104
B3	0	0.00	0.00

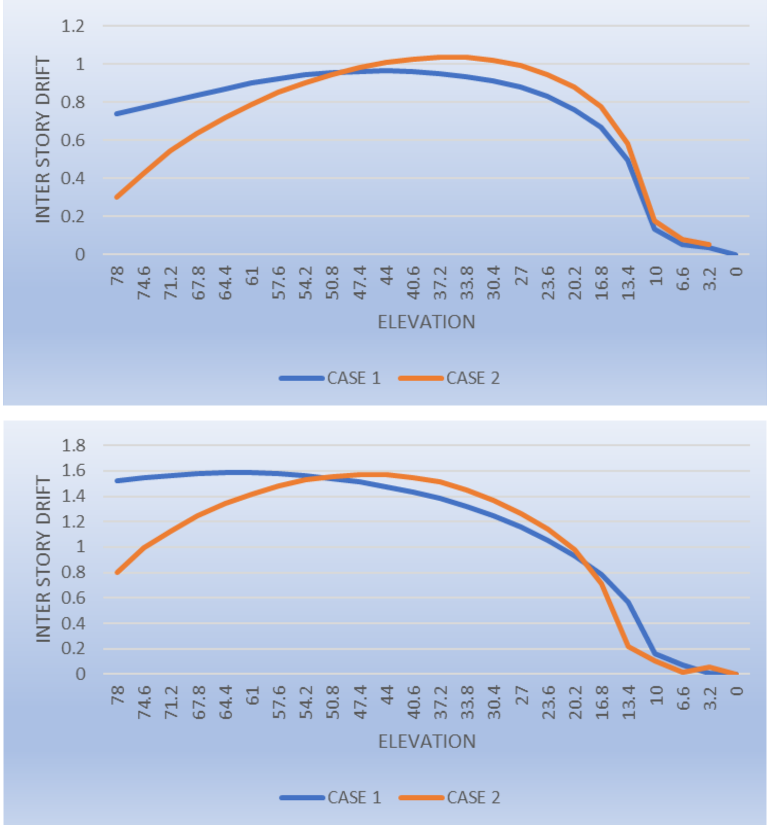

Fig. 9. Inter-storey drift for all cases along X and Y directions

Table 11. Total Displacement for all cases along X-direction

Storey	Elevation	Displacement Along X-Direction (mm)	
		Case 1	Case 2
20/F	78	57	54.3
10/F	44.0	28.6	31.7
G/F	10.0	0.561	0.832
B3	0.0	0.00	0.00

Table 12. Total Displacement for All Cases Y-direction

Storey	Elevation	Displacement Along Y-Direction (mm)	
		Case 1	Case 2
20/F	78	88.64	82.89
10/F	44.0	38.59	44.71
G/F	10.0	0.712	1.06
B3	0.0	0.00	0.00

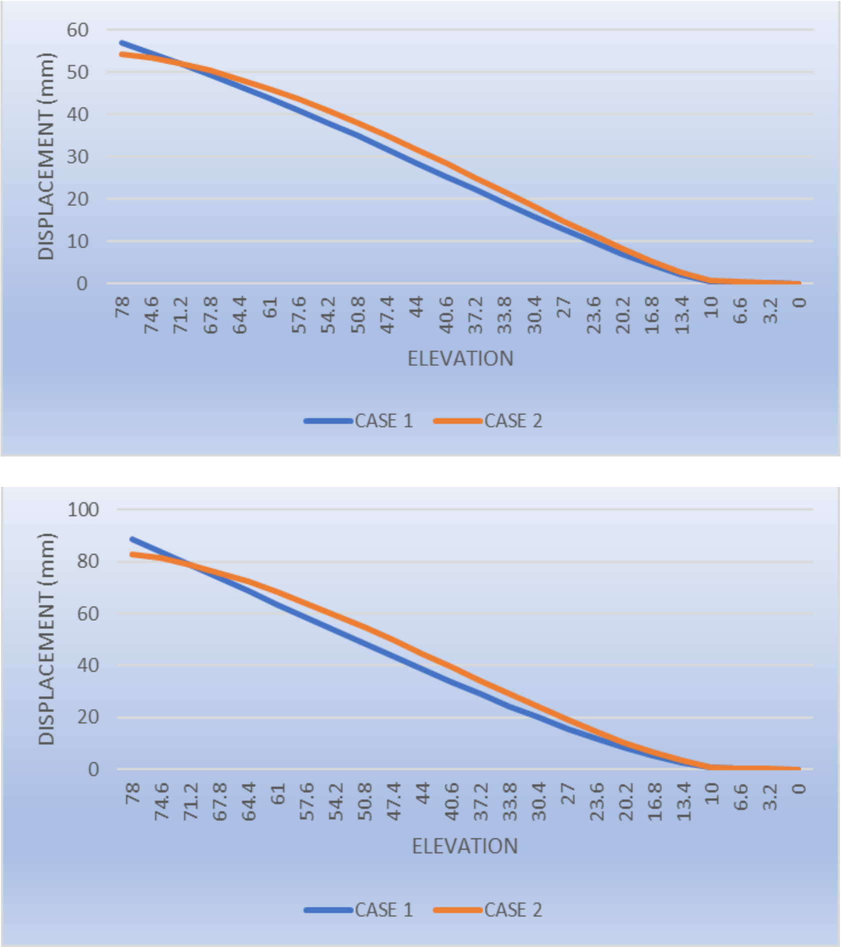

Fig. 10. Total displacement for all cases along X and Y directions

5. CONCLUSION

Based on the results of the analytical study, the following conclusions were drawn:

- The incorporation of reinforced concrete outriggers to high-rise buildings significantly improved structure's seismic response specifically in terms of modal period. Hence, considered to be one of the effective and practical option to enhance buildings performance under application of lateral forces.
- The result in terms of inter story drifts and displacement shows only slight difference between case 1 and case 2 which prompts to further conduct thorough investigation and simulation to record a more accurate result.

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2. **Version**: GPT-4
3. **Model**: GPT-4
4. **Source**: OpenAI

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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