



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJIRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 12, December 2024

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.524

9940 572 462

6381 907 438

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Evaluating Bracing Configurations in Offshore Structures under Multi-Load Conditions

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ABSTRACT: Offshore structures are critical in withstanding complex environmental loads such as gravity, earthquake, and wind forces. This research aims to compare the structural behaviour of three distinct bracing configurations—single bracing, double bracing, and knee bracing—under these loading conditions while considering varying bracing inclinations (0° , 20° , and 30°). The study evaluates key performance parameters, including time period, base shear, natural frequency, and displacement, using finite element modelling and time history analysis in SAP 2000. The results indicate that knee bracing demonstrates superior performance in terms of time period, natural frequency, and overall structural stability compared to the other configurations. The double bracing system exhibited optimal base shear resistance at a 30° inclination. Additionally, displacement analysis revealed that the double bracing configuration provides the highest resistance to deformation, while knee bracing maintained better structural response under dynamic load variations. Furthermore, steeper bracing angles improved overall stability, with a 30° bracing angle resulting in the least deformation across all configurations.

This study offers insights into optimal bracing patterns and their structural performance for offshore structures exposed to multi-load scenarios, contributing to the design and safety assessment of future offshore engineering projects

KEYWORDS: Offshore structures, Bracing configurations, Multi-load analysis, Structural stability

I. INTRODUCTION

Offshore platforms are crucial for various operations like navigation, ship loading/unloading, oil production, exploration, and bridge/causeway maintenance. These structures, exposed to extreme environmental conditions, present challenges in design and analysis. Typically constructed using steel and concrete, offshore platforms include piles as the foundation, jackets for support, and tops for accommodating equipment. They are among the tallest and heaviest structures on Earth.

Offshore platforms are categorized based on material types and substructure height: Gravity-based, Jacket, and Tension Leg Platforms (TLP). Gravity-based platforms are efficient in shallow depths (up to 50-60m). However, as the depth increases, their construction becomes uneconomical due to their massive weight. For deeper constructions (up to 100-140m), Jacket Platforms are more cost-effective. These platforms are made up of legs and a bracing system. In extremely deep sites (greater than 500m), Tension Leg Platforms are ideal. TLPs feature a pontoon structure supported by tensioned cables, which remain under constant tension.

Offshore structures face extreme environmental loads due to wind and wave action, making their analysis and design complex. Around 25-30% of the total project cost is allocated to construction, so even small savings in construction can lead to more economical designs. Optimization is vital for cost-effective and efficient offshore platform design. For instance, the Mumbai High field, an offshore oilfield located 176 km off the west coast of Mumbai in the Gulf of Cambay, showcases the significance of these structures in India's offshore oil industry.

II. LITERATURE SURVEY

Offshore structures, such as oil platforms and wind turbines, are essential for harnessing marine resources and advancing technology in harsh environments. Designing these structures requires accounting for dynamic forces like waves, wind, and seismic activity, ensuring structural stability and integrity. Harish N. et al. (1999) examined dynamic responses to wave and wind forces, revealing maximum deflections of 2.39 cm, emphasizing the need for dynamic analysis. Zulkipli Henry et al. (2013) focused on stress utilization and structural response under external loads in Malaysian waters, identifying critical components and the impact of wave loading. Poonam Mohan et al. (2013) analyzed a jacket platform at Mumbai High, providing insights for designing reliable structures under operational and ultimate limit states. Shehata E. et al. (2013) explored nonlinear response analysis, highlighting the platform's resilience to waves and storms. Behrouz Asgarian et al. (2013) studied seismic response using incremental dynamic analysis, suggesting improvements in bracing systems. Taha Nasser et al. (2014) optimized structural performance and weight using genetic algorithms, ensuring safety while minimizing costs. Faseela A. et al. (2015) optimized jacket weight and bracing configurations in the North Sea, demonstrating a 26.4% reduction in weight. Zolfaghari et al. (2015) simplified seismic assessment, reducing analysis time and providing a practical evaluation tool. Bipasha Das et al. (2017) and Shalini Rachel George et al. (2020) analyzed jacket platforms under environmental loading, emphasizing wave load dominance and the impact of water depth and wave height. Aishwarya Dengale et al. (2022) optimized jacket structures, considering wave and current forces for improved design efficiency.

III. METHODOLOGY

The methodology employed in this research involves the design, analysis, and evaluation of offshore steel structures subjected to various dynamic loads, including gravity, earthquake, and wind forces. The primary focus is on understanding the structural behavior of steel frameworks under the influence of ground motion and seismic events. The research is carried out using advanced computational tools such as SAP 2000 for finite element modeling and dynamic analysis.

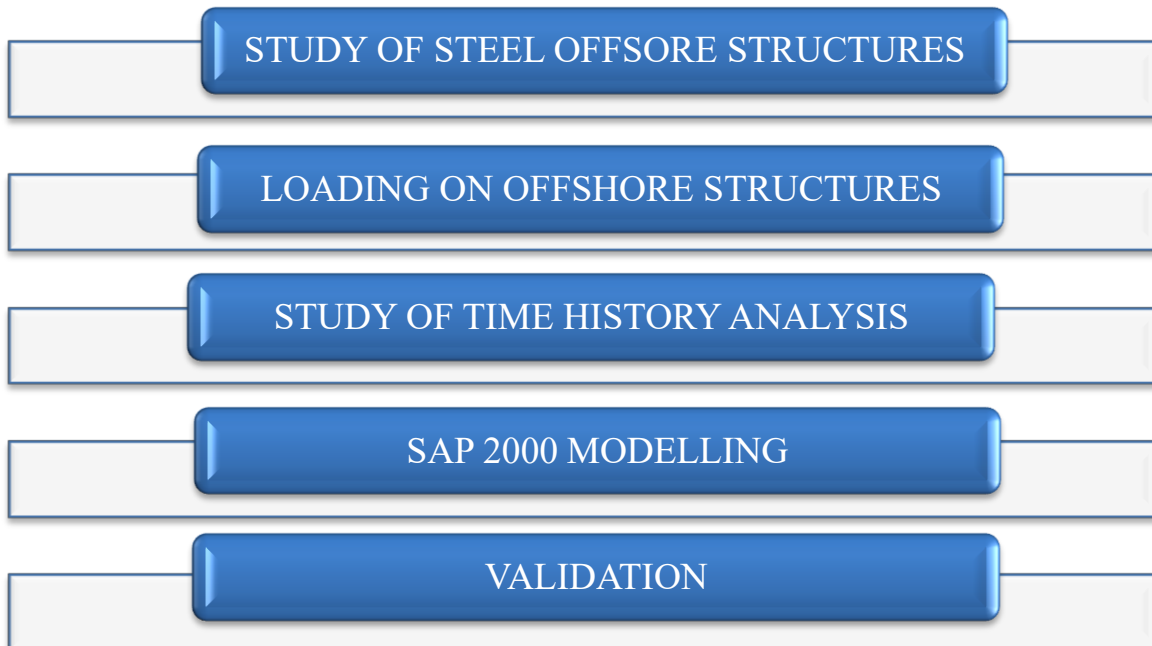


Figure 1: Flow Chart of Methodology

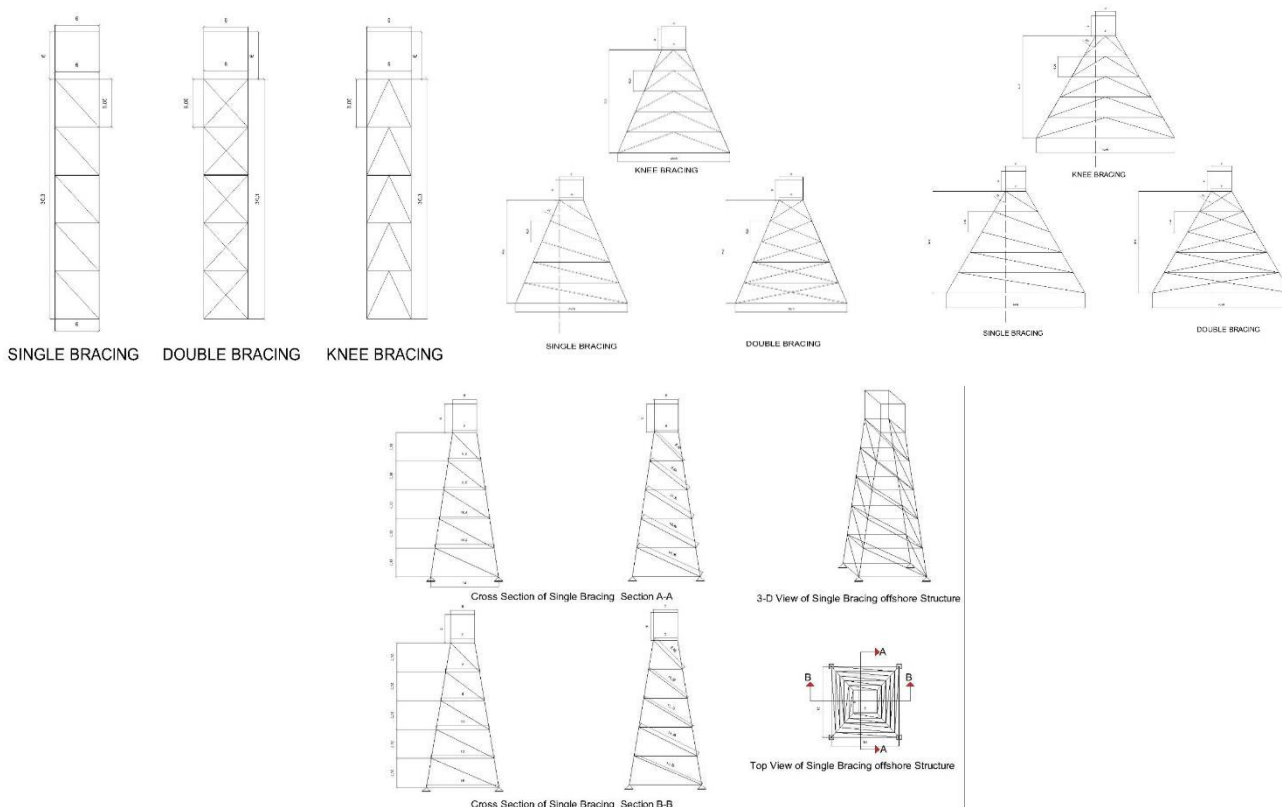


Figure 2: 2D drawing of structures

Three distinct bracing configurations, namely single bracing, double bracing, and knee bracing, are considered for this study. These configurations are designed to assess their performance in resisting different types of loads. The structures are modeled using SAP 2000, where finite element analysis (FEA) is performed to simulate the behavior of each configuration under gravity, wind, and earthquake loads. Each bracing type is tested with three different leg inclinations: 0°, 20°, and 30°. The objective is to evaluate the effectiveness of each bracing configuration in terms of stability and deformation. Time history analysis is employed to study the dynamic response of the structure under seismic ground motions. A synthetic ground motion record is used as the base motion for this analysis. The dynamic behavior is computed at discrete time steps, and the structure's maximum responses are considered to determine the impact of seismic forces. The analysis accounts for the base shear, displacement, time period, natural frequency, and other structural parameters. The dynamic approach is essential for studying tall structures with torsional asymmetries, which cannot be analyzed accurately with static methods. The seismic forces acting on the structures are calculated using the base shear formula provided in IS 1893:2002, taking into account seismic zone factors, the importance factor (I), and the response reduction factor (R). A response spectrum analysis is then performed to compute the maximum response of the structure. This analysis evaluates the behavior of the structure under earthquake-induced vibrations, accounting for all vibration modes and their independent responses. The dynamic properties of ground motions—peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD)—are analyzed to categorize seismic events based on their frequency content. Ground motion records are classified into high, medium, and low-frequency categories using the PGA/PGV ratio. The frequency content influences the structural response, especially for different building heights and seismic zones. The material properties of the steel and concrete used in the structure are based on the specifications outlined in IS-456 and IS-1893:2002. Steel material used in this research includes A992Fy50 (Fy=50ksi, Fu=65ksi), and the properties of the concrete are as per IS-456. These material properties, along with damping coefficients, thermal expansion coefficients, and elastic moduli, are incorporated into the analysis models to ensure realistic simulation of the structure's response under dynamic loading. The research involves the collection of seismic data from various earthquake events, including the 1979 Imperial Valley-06 (Holtville Post Office), 1957 San Francisco (Golden Gate Park), and the 1992 Landers (Fort Irwin) earthquake. These records are analyzed for their ground motion characteristics, such as peak acceleration, velocity, and displacement,

which are used to assess the structural response. The data is classified based on frequency content and used to simulate different seismic loading scenarios in the model.

By employing this methodology, the study aims to identify the most effective bracing configuration and evaluate the seismic resilience of offshore structures under varying seismic conditions. The results of the analysis provide valuable insights into the structural behavior of offshore frameworks and contribute to enhancing the safety and stability of these vital infrastructures.

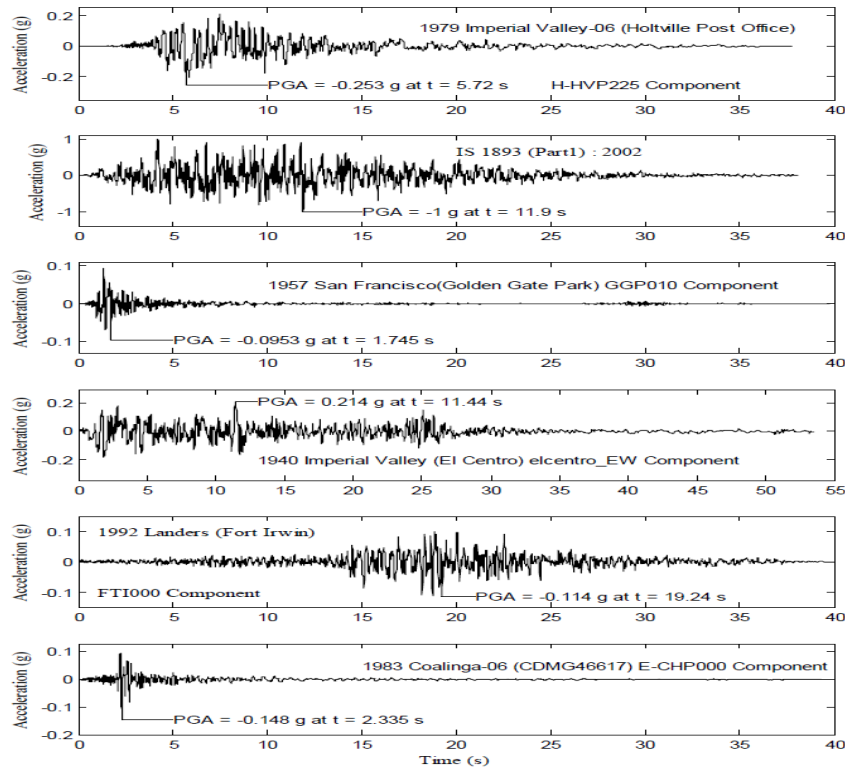
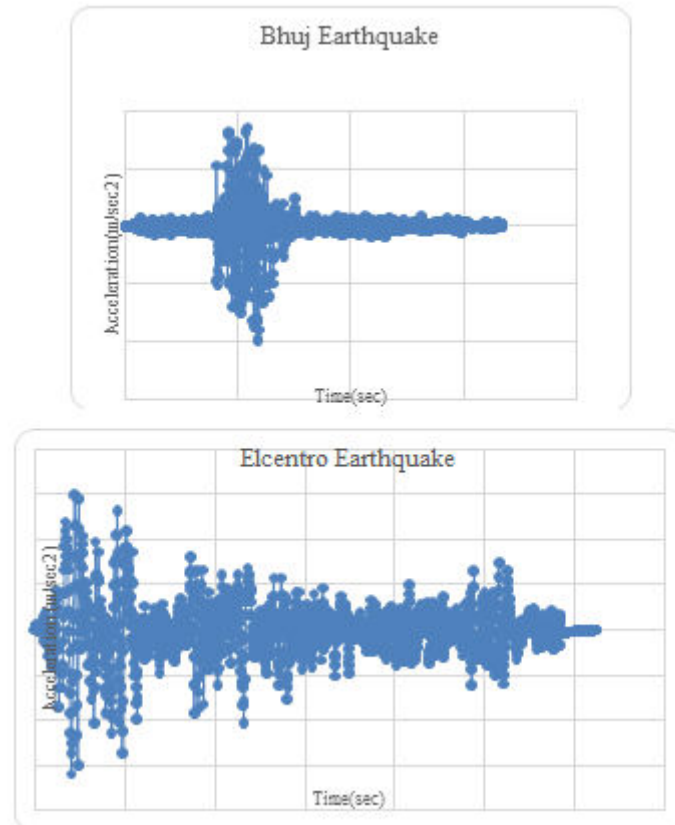


Figure 3: Peak ground acceleration(PGA)

Concrete Properties		Steel Bar Properties	
Unit weight (γ_{cc})	25 (kN/m ³)	Unit weight (γ_{ss})	76.9729 (kN/m ³)
Modulus of Elasticity (EE_{cc})	22360.68 (MPa)	Modulus of elasticity (EE_{ss})	2×10^5 (MPa)
Poisson ratio (ν_{cc})	0.2	Poisson ratio (ν_{ss})	0.3
Thermal coefficient (α_{acc})	5.5×10^{-6}	Thermal coefficient (α_{ass})	1.170×10^{-6}
Shear modulus (GG_{cc})	9316.95 (MPa)	Shear modulus (GG_{ss})	76923.08 (MPa)
Damping ratio (ζ_{cc})	5 (%)	Yield strength (FF_{yy})	415 (MPa)
Compressive strength (FF_{cc})	30 (MPa)	Tensile strength (FF_{uu})	485 (MPa)

**Figure 4: Data Collected EL-CENTRO**

IV. EXPERIMENTAL RESULTS

The dynamic behavior of the offshore steel structure was analyzed for different bracing systems (single, double, and knee) and bracing angles (0° , 20° , and 30°) under seismic loading using the El-Centro earthquake data.

The time period (T) analysis revealed that knee bracing systems had the highest time period, indicating a lower vibration frequency and better damping characteristics. In contrast, the single bracing system, particularly at 30° , had a shorter time period, leading to higher frequencies of vibration and reduced energy dissipation.

Natural frequency analysis showed that knee bracing systems had the highest natural frequencies, reducing the likelihood of resonance during seismic events. This suggests that knee bracing provides more stability and a more favorable response to ground shaking. On the other hand, single and double bracing systems at 30° exhibited lower natural frequencies, making them more prone to resonance with seismic excitation.

Displacement analysis along the X and Y axes revealed that knee bracing systems experienced the least displacement, demonstrating superior control over structural movement. Single bracing, especially at 30° , showed significantly higher displacements, indicating greater vulnerability to deformation under seismic loading. Double bracing systems exhibited moderate displacement control, outperforming single bracing but not reaching the performance level of knee bracing.

Overall, knee bracing proved to be the most effective in terms of reducing displacement and providing stability, while single and double bracing systems showed increased displacement and a higher risk of resonance, particularly at steeper angles.

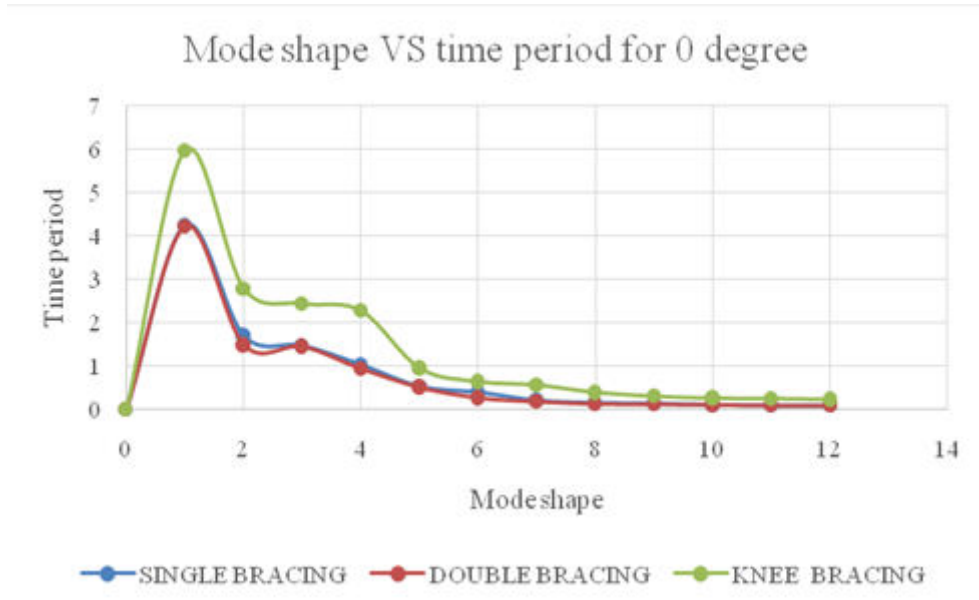


Figure 5: Mode Shape v/s Time period for 0 Degree

The graph represents variation of time period with respect to different mode shapes where in knee bracing has time period 6 at mode shape 1 which is lesser in double and single bracing of 30% and 29% respectively. Further it is observed that the time period is zero at 12th mode shape in all the bracing patterns.

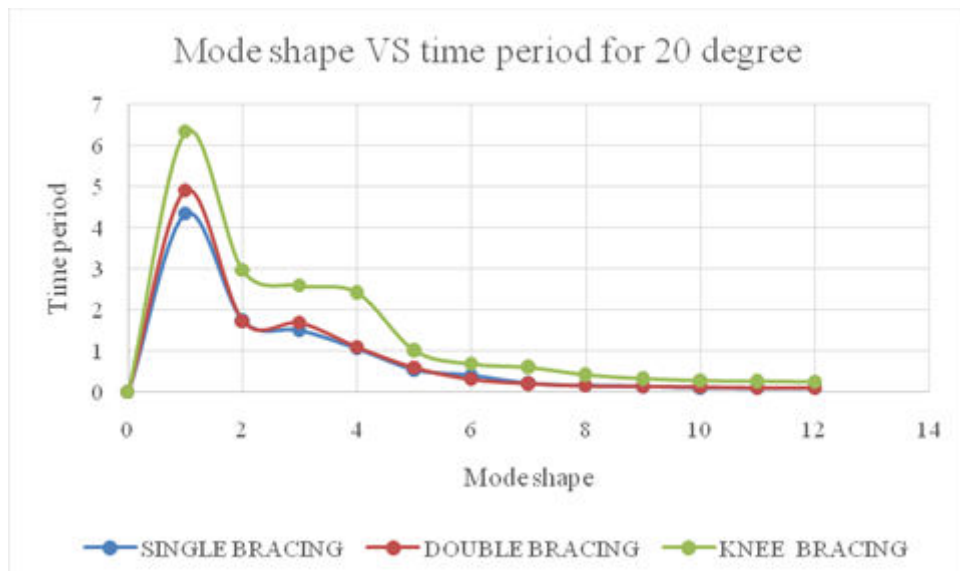


Figure 6: Mode Shape v/s Time period for 20 Degree

The graph represents variation of time period with respect to different mode shapes where in knee bracing has time period 6 at mode shape 1 which is lesser in double and single bracing of 32% and 22% respectively. Further it is observed that the time period is zero at 12th mode shape in all the bracing patterns.

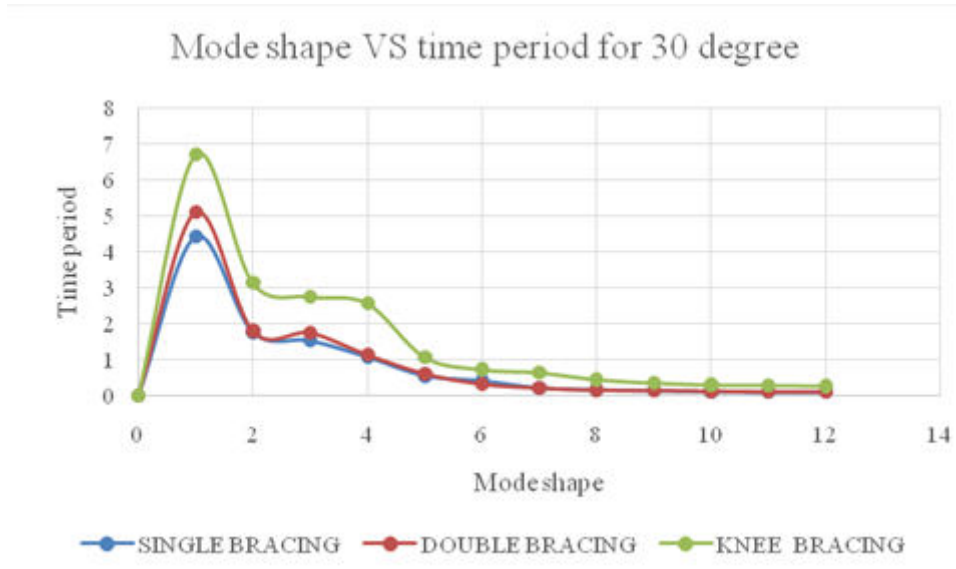


Figure 7: Mode Shape v/s Time period for 30 Degree

The graph represents variation of time period with respect to different mode shapes where in knee bracing has time period 6 at mode shape 1 which is lesser in double and single bracing of 34% and 24% respectively. Further it is observed that the time period is zero at 12th mode shape in all the bracing patterns

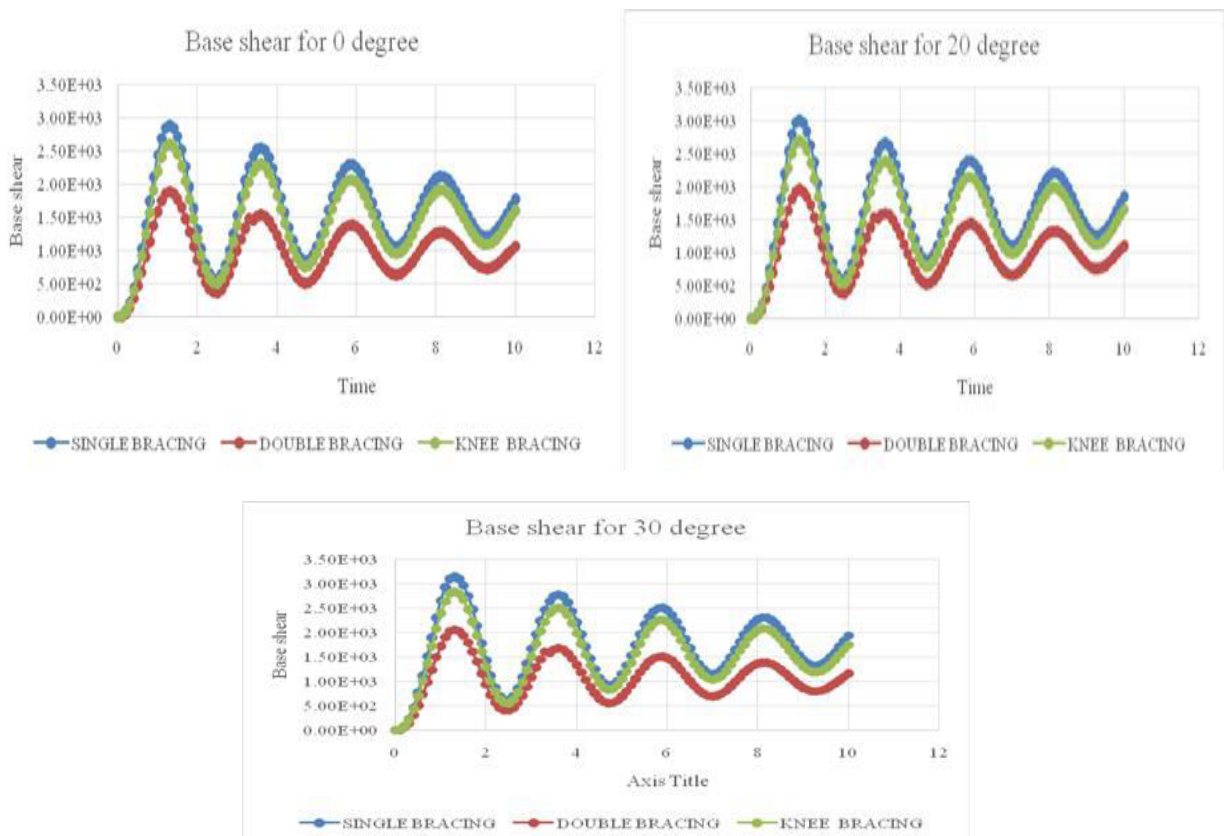


Figure 8: Base Shear v/s time period for 0, 20 and 30 degree inclination

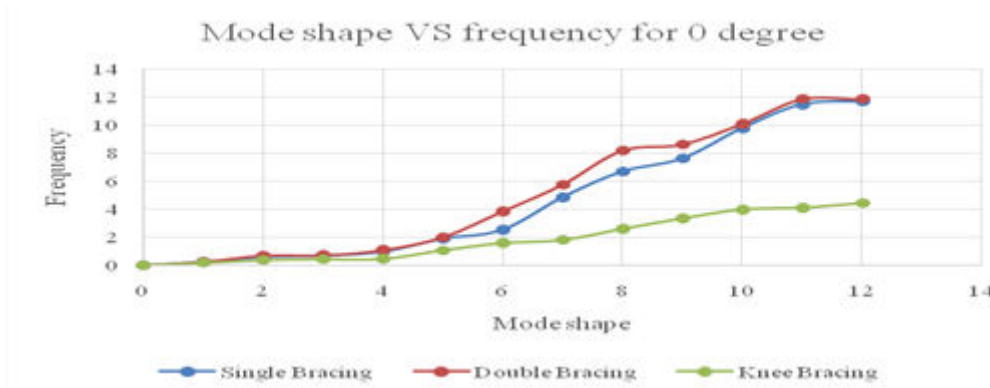


Figure 9: Mode Shape v/s Natural frequency for 0 degree

In this graph maximum natural frequency is in double bracing is 12. The difference between double and single bracing is 1%. Lowest value observed in Knee bracings and when compare with single bracing its 37%. graph clearly show that Double Bracing has the maximum natural frequency, with only a slight decrease for Single Bracing and a significant drop for Knee Bracing.

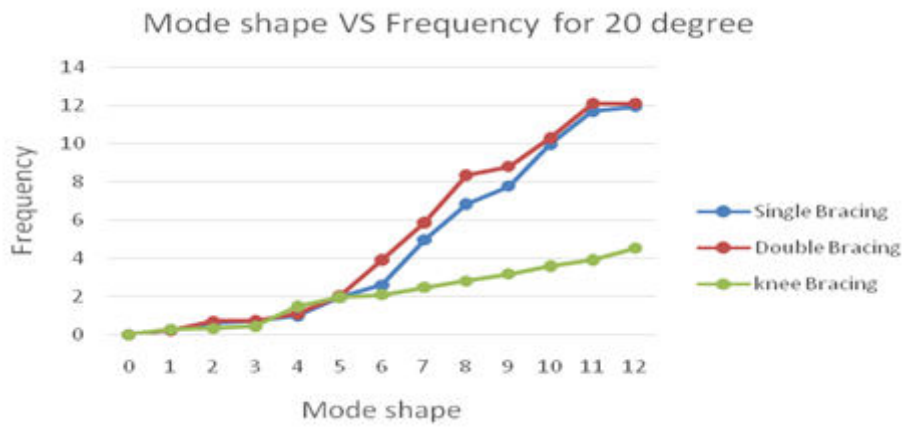


Figure 10: Mode Shape v/s Natural frequency for 20 degree

The graph displays the maximum natural frequency of 12 in double bracing. There is 1% distinction between single and double bracing. Knee bracings have the lowest value, which is 38% when compared to a single bracing. With only a minor decline for single bracing and a large drop for knee bracing, the graph unmistakably demonstrates that double bracing has the maximum natural frequency.

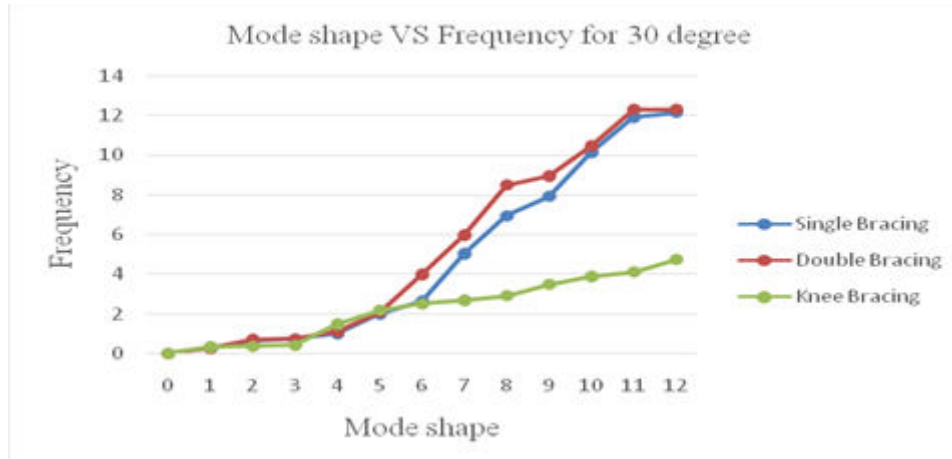


Figure 11: Mode Shape v/s Natural frequency for 30 degree

In this graph maximum natural frequency is in double bracing is 12. The difference between double and single bracing is 1%. Lowest value observed in Knee bracings and when compare with single bracing its 37%. graph clearly show that Double Bracing has the maximum natural frequency, with only a slight decrease for Single Bracing and a significant drop for Knee Bracing

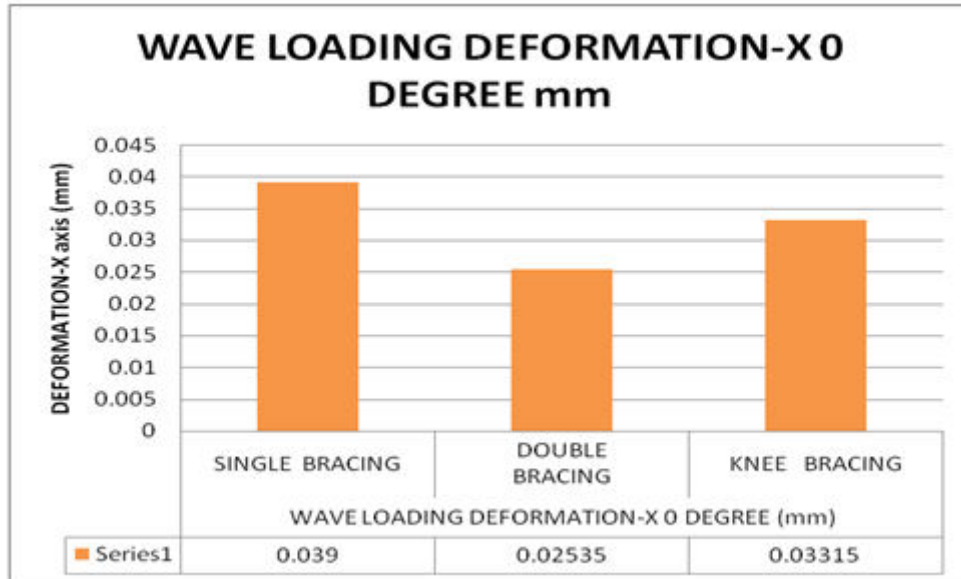


Figure 12: Displacement-X axis for 0 Degree inclination

As a result, compared to single bracing, knee bracing offers a more robust construction and reduces the maximum deformation in the X direction at 0 degrees by 18.75%.

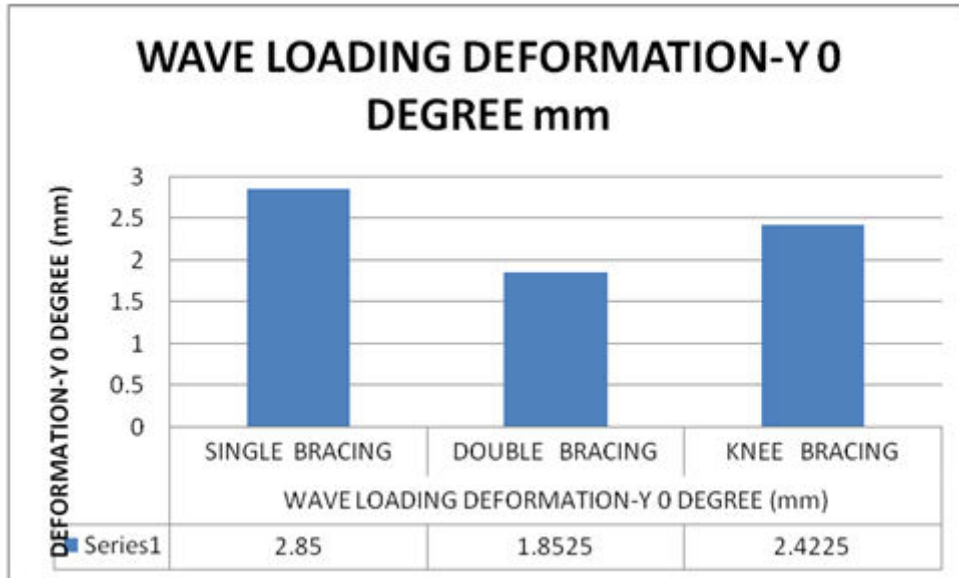


Figure 13: Displacement-Y axis for 0 Degree inclination

In this graph, the maximum deformation-Y at 0 degrees is in single bracing, which is 2.85 mm. Due to its ability to deformation, the knee bracing system outperforms the single bracing system. In particular, knee bracing, when compared to single bracing at 0 degrees, reduces the maximum deformation by approximately 15%.

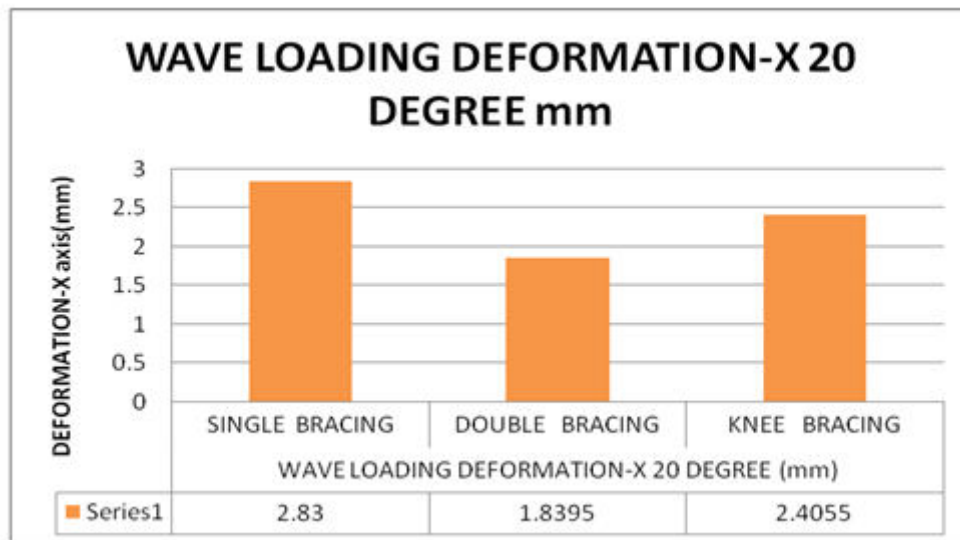


Figure 14: Displacement-X axis for 20 Degree inclination

The knee bracing configuration reduces the deformation compared to single bracing. Specifically, the deformation with knee bracing is around 15% less than the deformation observed with single bracing, meaning knee bracing offers better structural performance in terms of reducing displacement under the given conditions.

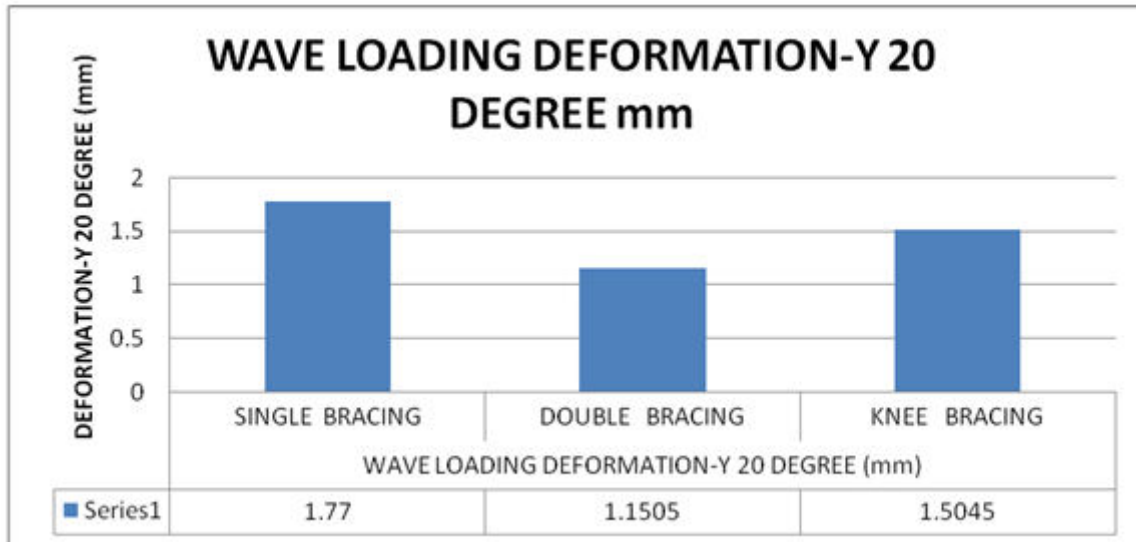


Figure 15: Displacement-Y axis for 20 Degree inclination

The greatest Deformation-at Y axis in single bracing in this graph, at 20 degrees is 1.77 mm. There is around a fifteen percent difference between knee bracing and single bracing.

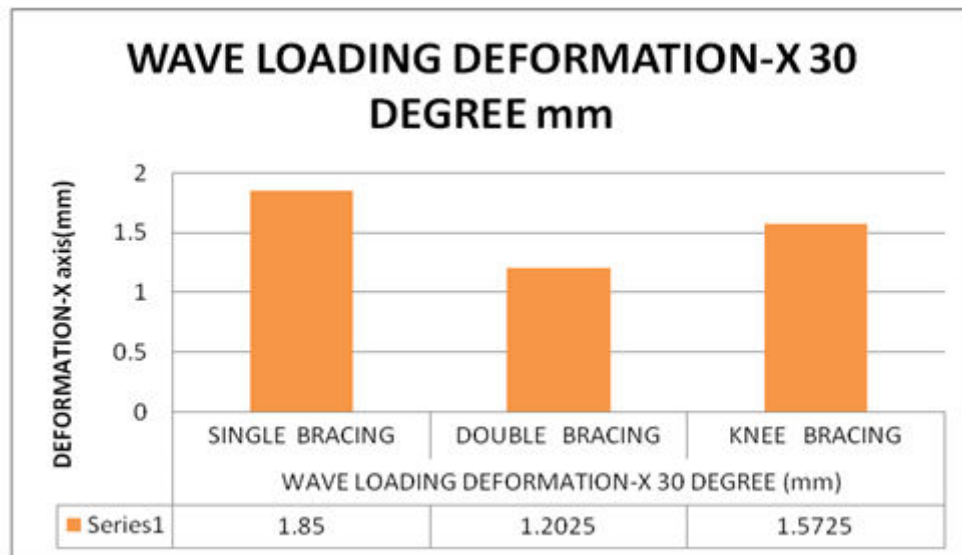


Figure 16: Displacement-X axis for 30 Degree inclination

In the analysis of structural deformations under different bracing systems, it was observed that at a 30-degree angle, the maximum deformation X-axis in the single bracing configuration is 1.85 mm. This deformation value represents the maximum amount of displacement experienced by the structure due to applied loads or forces.

When comparing the single bracing system to the knee bracing system, it is noted that the knee bracing configuration results in a reduction in deformation. Specifically, the difference in deformation between the single bracing and knee bracing systems is approximately 15%. This indicates that knee bracing is more effective at reducing the maximum deformation compared to single bracing.

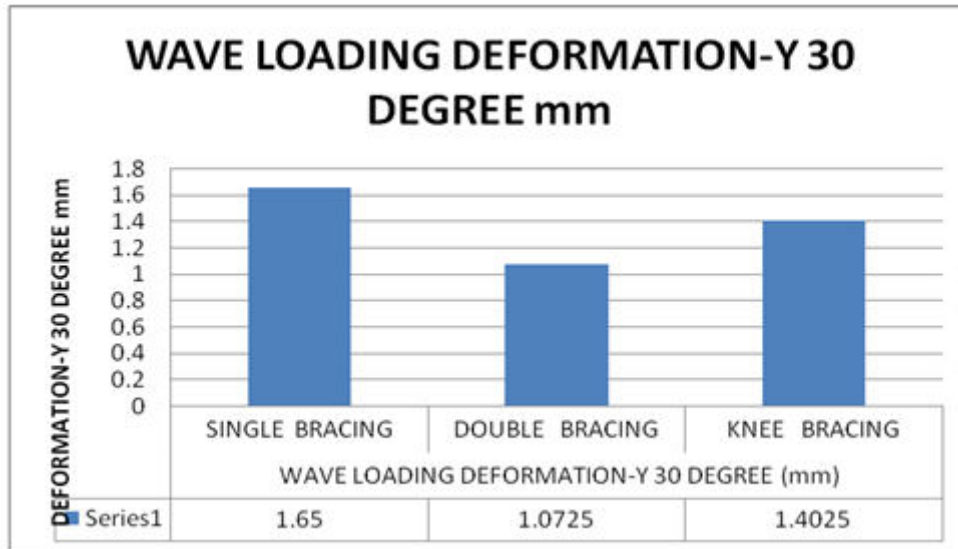


Figure 17: Displacement-Y axis for 30 Degree inclination

When comparing single bracing to knee bracing, the deformation observed with single bracing is approximately 15% greater. The maximum amount of deformation or displacement measured along the Y-axis when the structure is subjected to an angle of 30 degrees.

The analysis of natural frequency and time period across various bracing systems revealed that knee bracings exhibit the lowest values. This is due to their reduced lumped mass, leading to lower stiffness and increased flexibility compared to single and double bracings. These characteristics make knee bracings less suitable for applications requiring higher rigidity and resistance to dynamic loads.

Base shear analysis showed that all bracing configurations produced similar results under the El Centro earthquake motion. This consistency is expected, as the seismic load impacts all models uniformly. Minor differences observed are attributed to variations in mass distribution and stiffness across the bracing systems.

Deformation analysis highlighted that double bracings experience the least deformation, especially at a 30-degree inclination. This superior stiffness and stability make double bracings an ideal choice for scenarios requiring minimal deflection and enhanced structural integrity.

In comparing bracing systems, double bracing consistently demonstrated the highest natural frequencies, outperforming single bracing by a margin of 1-4%. This indicates greater stiffness and better dynamic performance. Conversely, knee bracings exhibited the lowest natural frequencies, emphasizing their increased flexibility and reduced stiffness. These differences are critical for structural design decisions, particularly in environments with significant dynamic loads where stiffness and frequency characteristics are key considerations.

V. CONCLUSION

The present study analyzes the behavior of an offshore structure subjected to gravity, earthquake, and wind loads, focusing on three different bracing configurations: single bracing, double bracing, and knee bracing. The study evaluates key parameters to identify the most effective bracing configuration with varying leg inclinations (0°, 20°, and 30°): time period, base shear, natural frequency, and displacement.

Finite element analysis was performed using SAP2000, followed by time history analysis for the three bracing configurations. The findings show that the knee bracing configuration exhibited the longest time period in the desired

mode shapes, indicating better structural performance compared to the single and double bracing configurations. Knee bracing consistently outperformed the other bracing patterns in terms of overall structural performance.

The study also revealed that the maximum base shear for the 30° single bracing model was 3.096 kN, while for the double bracing, it was 2.02 kN, demonstrating that the 30° double bracing configuration had better resistance and base shear. Additionally, knee bracing had a higher natural frequency, implying a shorter time period and better stability compared to the other configurations.

Regarding deformation, the single bracing configuration at a 30° angle showed the highest deformation along both the X and Y axes, with approximately 15% more deformation than knee bracing and 35% more than double bracing. Double bracing displayed the highest resistance to deformation. For all angle variations (0°, 20°, and 30°), the least deformation occurred at 30°, suggesting that a steeper angle improves structural stability.

In conclusion, knee bracing provides superior performance, while double bracing offers excellent resistance to deformation and base shear. A 30° inclination optimizes the structure's stability.

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