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Structural Performance and Stability Optimization of Elevated Water Tank Frames Using Different Bracing Types

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***Abstract*—Elevated water tanks are essential components in urban and rural infrastructure, providing continuous water supply and maintaining hydraulic pressure. The structural safety and stability of these tanks depend largely on the performance of their supporting frame under lateral loads such as wind and earthquakes. This study focuses on the comparative analysis of elevated water tank staging systems with different bracing configurations namely, Model 1: Without Brace, Model 2: Diagonal Bracing, Model 3: Knee Bracing, and Model 4: Cross Bracing.**

Using finite element analysis, each model was analyzed under identical loading conditions to evaluate its lateral displacement, base shear, bending moment, and overall structural stability. The results revealed that the inclusion of bracing systems significantly enhances the lateral stiffness and reduces top displacement compared to the unbraced frame. Among all configurations, cross bracing exhibited the highest efficiency in minimizing deformation and improving seismic resistance, followed by diagonal and knee bracing systems. The study concludes that selecting an appropriate bracing arrangement can substantially improve the seismic performance and economic design of elevated water tank structures. The findings provide valuable insights for engineers to optimize design parameters and ensure structural safety under dynamic loading conditions.

***Index Terms*—Elevated Water Tank; Bracing System; Structural Analysis; STAAD.Pro**

I. INTRODUCTION

Elevated water tanks are essential public utility structures used for storing and supplying water under adequate pressure to meet domestic, industrial, and firefighting demands. They are widely adopted in urban and rural areas due to their ability to provide consistent water distribution even when pumping systems fail or during power outages.[4] The elevated tank is typically supported by a staging structure composed of columns and horizontal braces designed to withstand various loads including dead, live, wind, and seismic forces. The overall safety and functionality of such tanks largely depend on the stability and rigidity of the supporting frame system. [5]

In recent decades, several failures of elevated water tanks during earthquakes in India and worldwide have emphasized the importance of studying their dynamic behavior. The lateral stiffness of the staging, which is primarily influenced by the type of bracing adopted, plays a critical role in determining the seismic performance of these structures. [8] Insufficient stiffness may lead to large displacements, excessive stresses in members, and potential collapse. Therefore, understanding and optimizing the behavior of different bracing configurations is vital for ensuring both safety and economy. [9]

A. Importance of Bracing Systems

Bracing systems serve as key structural components that enhance the lateral strength and stability of the staging by forming an efficient load-transfer mechanism. Depending on the arrangement and geometry, bracing can control sway, reduce slenderness effects, and minimize deflections under lateral loads. Commonly used bracing types include diagonal bracing, knee bracing, cross bracing (X-type), and unbraced or moment-resisting systems. Each configuration offers distinct advantages in terms of stiffness, ductility, and construction feasibility. An optimal bracing layout can significantly improve seismic performance while minimizing material consumption and cost. [5]

II. STATE OF DEVELOPMENT

G. W. Housner et al. (1963) developed simplified formulae to estimate earthquake forces in water tanks, considering them as two-mass systems where impulsive and convective pressures act due to fluid motion relative to the tank, highlighting the need for detailed dynamic analysis of sloshing effects. S. C. Dutta et al. (2000) analyzed earthquake-induced failures of elevated water tanks and found that accidental eccentricities, sloshing, and non-uniformities could cause torsional vibrations and localized damage. B. Devadanam et al. (2015) concluded that frame-staged reinforced concrete elevated tanks exhibit better seismic resistance than shaft-staged ones due to higher energy absorption capacity, analyzing seismic responses under different parameters using SAP2000. S. M. Maidankar et al. (2015) studied the seismic performance of tanks with different bracing systems, finding that cross and radial bracing significantly reduce base shear and displacement. R. Livaoglu et al. (2008) showed through FE modeling that soil–structure interaction notably affects sloshing response, particularly for soft soils. P. V. Muthu et al. (2016) emphasized the importance of including sloshing effects in seismic design of Intze-type tanks, observing up to 40–56% increases in dynamic responses. S. Bozorgmehrnia et al. (2013) performed time-history analysis of elevated tanks, showing that earthquake frequency content and tank filling levels significantly influence base shear and sloshing displacements. K. J. Dona Rose et al. (2015) conducted nonlinear time-history analysis using ANSYS and confirmed that sloshing effects must be considered for tanks under different fill conditions. S. A. Patil et al. (2016) found that sloshing acts as a damping mechanism, reducing vibration amplitude but depending mainly on staging height rather than water volume. M. V. Waghmare et al. (2013) demonstrated that sloshing displacement increases with water depth and staging height, stressing the need to study h/d ratios. S. S. Besekar et al. (2014) compared static and dynamic analysis results, highlighting that sloshing frequency strongly influences tank response. S. K. Jangave et al. (2014) modeled impulsive and convective masses as one- and two-mass systems, finding significant effects of tank capacity and earthquake records on displacement and base shear. D. Virkhare et al. (2015) used pushover analysis to study staging behavior and plastic hinge formations under varying parameters. M. Masoudi et al. (2012) evaluated response modification factors (R) for shaft and frame-staged tanks, proposing improved modeling for seismic design. F. Omidinasab et al. (2008) applied performance-based design to assess seismic vulnerability under multiple earthquake records, while A. M. Jabbar et al. (2012) compared different bracing systems using SAP2000, concluding that cross and radial bracing improve seismic performance by reducing base shear and overturning moments. Overall, the literature collectively emphasizes that sloshing, staging configuration, soil–structure interaction, and bracing type significantly influence the seismic response and safety of elevated water tanks.

III. PROBLEM STATEMENT

Many existing elevated water tanks, particularly those designed using conventional methods, may not meet modern performance criteria under dynamic loading. Inadequate lateral stiffness or poorly arranged bracing systems can lead to excessive vibration, instability, or even collapse during severe seismic events. Although numerous studies have examined the seismic response of tank staging, limited research focuses on comparing different bracing types systematically using advanced analytical tools and optimization techniques. Hence, there is a need to evaluate the effect of various bracing configurations on structural performance parameters such as base shear, lateral displacement, natural period, and stress distribution, and to identify the most efficient and economical configuration.

- L = 12m
- B = 6m
- H= 4m
- Beam size - 300x600
- Column size - 350x750

- Earthquake zone - III
- Time history – Bhuj
- Soil – Medium stiff
- Depth of Foundation - 1.5m
- Concrete – M30

IV. RESEARCH DESIGN

The study involves developing finite element models of elevated water tank structures using software such as ETABS. The models are analyzed under gravity, wind, and seismic loads as per relevant Indian Standards (IS 875, IS 1893, IS 3370, and IS 456). Different bracing systems are applied to the same geometry to ensure a uniform basis of comparison. The parameters obtained from static and dynamic analyses, such as maximum displacement, stresses, and base shear, are compared to assess relative performance. Optimization techniques are then used to minimize material usage while maintaining structural stability and safety.

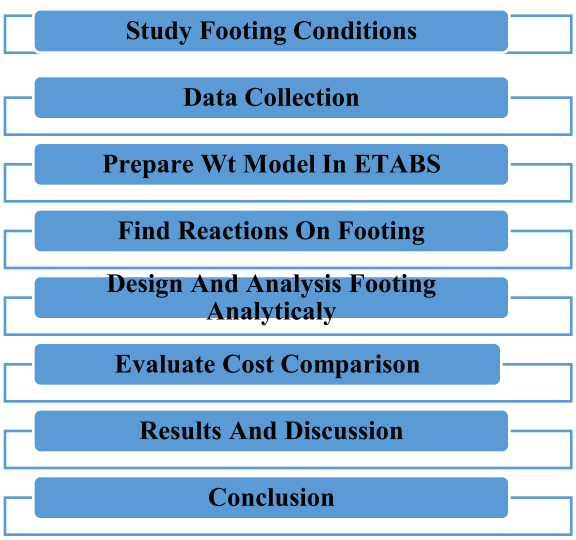


Table 1. Model Details

MODEL 1	Without Brace
MODEL 2	Diagonal Bracing
MODEL 3	Knee Bracing
MODEL 4	Cross Bracing

Table 1 presents the details of different analytical models of elevated water tanks considered in the study. Model 1 represents a tank without any bracing system, while Models 2, 3, and 4 incorporate diagonal, knee, and cross bracing configurations respectively to study their effect on seismic performance.

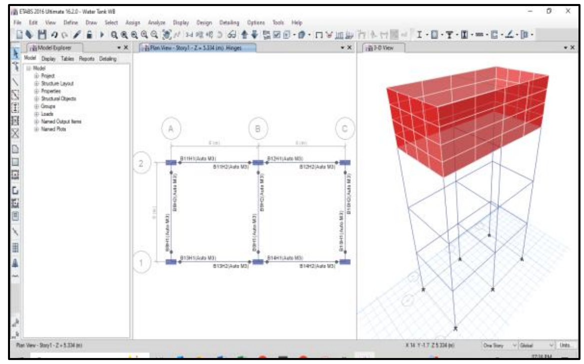


Fig 1 hinges provide on without brace model-1

Figure 1 shows the hinge locations provided in Model 1, which is the elevated water tank without any bracing system. The figure illustrates the points where hinges are introduced to simulate realistic joint behavior and assess the structural response under seismic loading

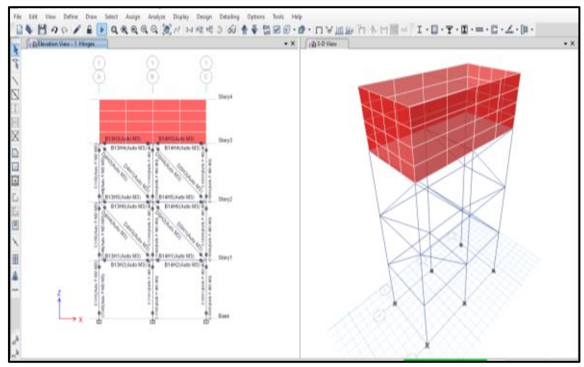


Fig 2 hinges provide on Diagonal Bracing

Figure 2 illustrates the hinge locations in the elevated water tank with diagonal bracing (Model 2). The figure shows how hinges are assigned at key joints to represent possible rotation and deformation points, helping to evaluate the effect of diagonal bracing on the structural performance during seismic loading.

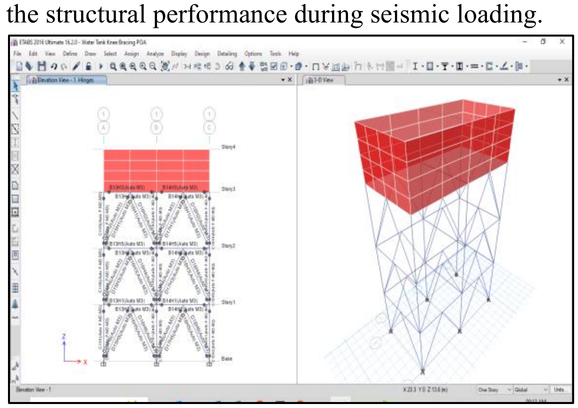


Fig 3 hinges provide on Knee Bracing

Figure 3 shows the hinge locations in the elevated water tank with knee bracing (Model 3). The hinges are placed at critical joints of the staging to represent realistic rotational behavior and to analyze the influence of knee bracing on the tank's seismic performance.

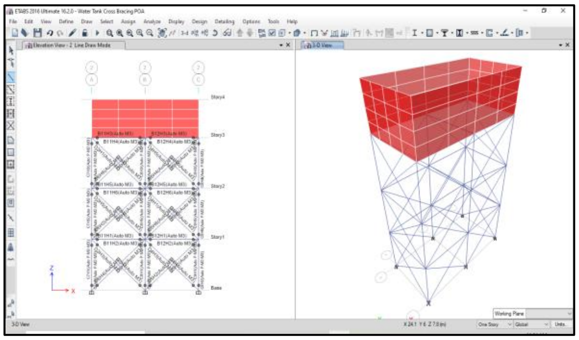


Fig 4 hinges provide on Cross Bracing

Figure 4 depicts the hinge locations in the elevated water tank with cross bracing (Model 4). Hinges are provided at crucial connection points of the staging to simulate joint rotations and to assess how the cross bracing configuration enhances the structure's stability and seismic resistance.

V. RESULT FOR PUSHOVER CURVE

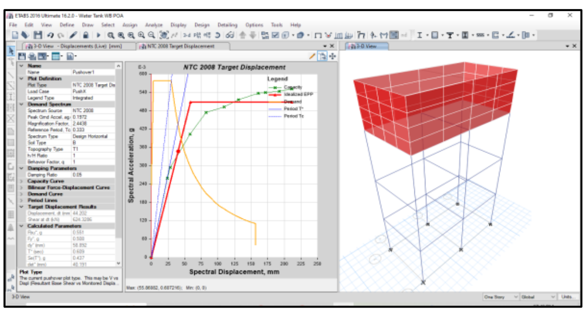


Fig 5 Pushover Curve Without Brace

Figure 5 presents the pushover curve for the elevated water tank without bracing (Model 1). The curve illustrates the relationship between base shear and roof displacement, showing the structural performance, stiffness degradation, and ultimate capacity of the unbraced model under lateral seismic loading.

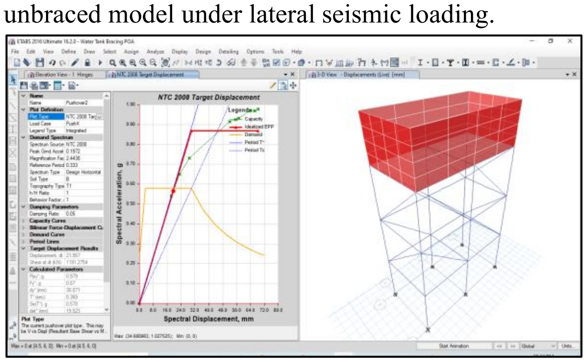


Fig 6 Pushover Curve Diagonal Bracing

Figure 6 shows the pushover curve for the elevated water tank with diagonal bracing (Model 2). The graph represents the variation of base shear with roof displacement, indicating improved stiffness, higher load-carrying capacity, and better seismic performance compared to the unbraced model.

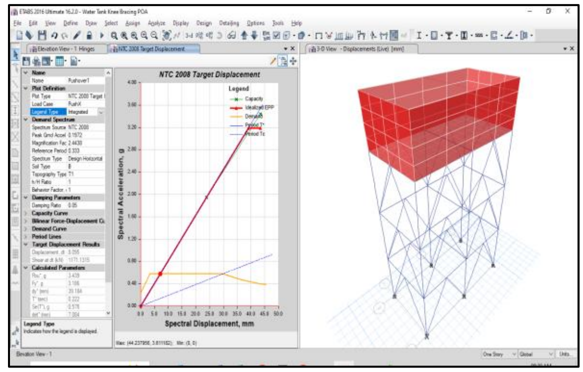


Fig 7 Pushover Curve Knee Bracing

Figure 7 illustrates the pushover curve for the elevated water tank with knee bracing (Model 3). The curve demonstrates the relationship between base shear and roof displacement, showing enhanced ductility and moderate improvement in lateral strength compared to the unbraced structure.

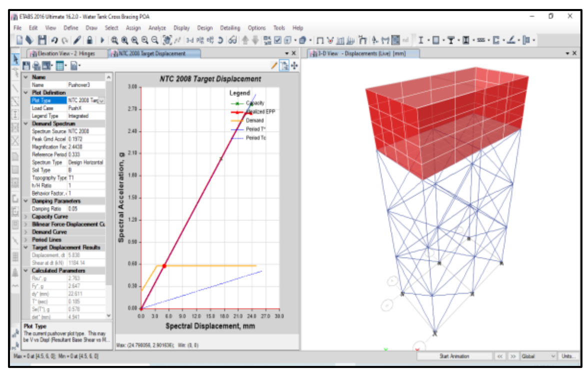


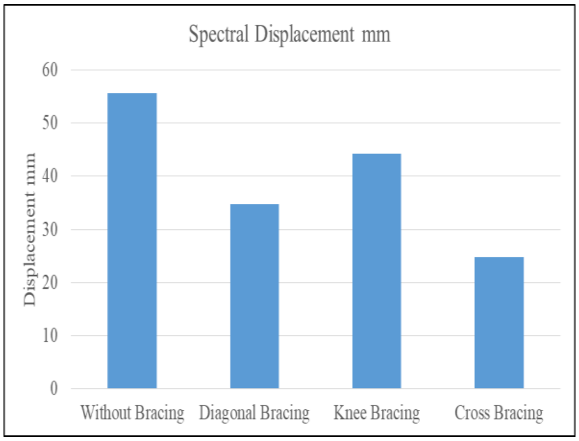
Fig 8 Pushover Curve Cross Bracing

Figure 8 presents the pushover curve for the elevated water tank with cross bracing (Model 4). The graph depicts the base shear versus roof displacement relationship, indicating that the cross-braced model exhibits the highest stiffness, strength, and seismic performance among all the analyzed configurations.

Table 2 Spectral Displacement

Spectral Displacement			
Without Bracing	Diagonal Bracing	Knee Bracing	Cross Bracing
55.66	34.68	44.23	24.79

Table 2 presents the spectral displacement values for elevated water tank models with different bracing configurations.



Graph 1 Spectral Displacement

Graph shows that the unbraced frame has the highest spectral displacement (55.66 mm), indicating poor lateral stiffness. Diagonal (34.68 mm) and knee bracing (44.23 mm) reduce displacement, while cross bracing gives the lowest value (24.79 mm), showing the best seismic performance and stability.

VI. RESULT FOR STORY SHEAR

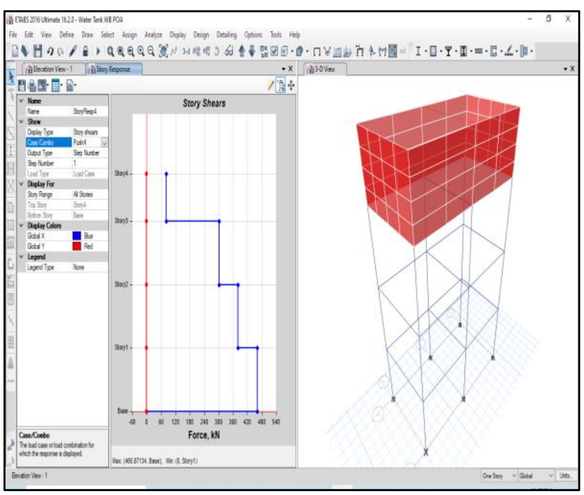


Fig 9 Story Shear without Brace Model

Figure 9 shows the story shear distribution for the elevated water tank without bracing (Model 1). The figure illustrates how lateral shear forces are transferred through the staging levels, indicating higher shear concentration at the lower stories due to the absence of lateral stiffness provided by bracing.

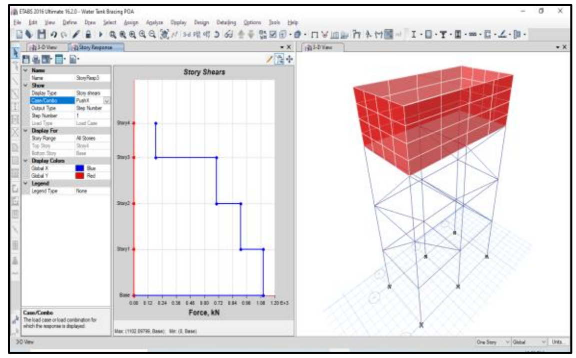


Fig 10 Story Shear Diagonal Brace Model

Figure 10 illustrates the story shear distribution for the elevated water tank with diagonal bracing (Model 2). The figure shows improved lateral load distribution and reduced shear demand on lower stories, indicating that diagonal bracing enhances stiffness and overall seismic resistance compared to the unbraced model.

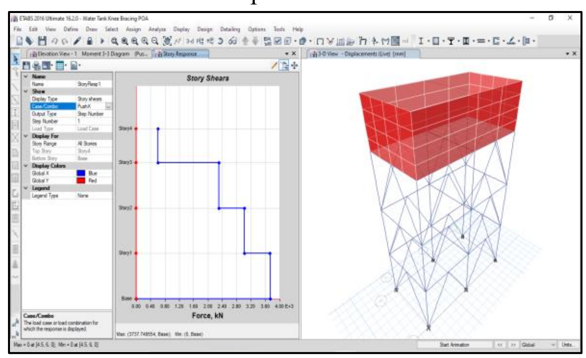


Fig 11 Story Shear Knee Brace Model

Figure 11 presents the story shear distribution for the elevated water tank with knee bracing (Model 3). The figure indicates a more uniform shear transfer through the staging, showing that knee bracing provides moderate improvement in lateral stiffness and stability under seismic loading conditions.

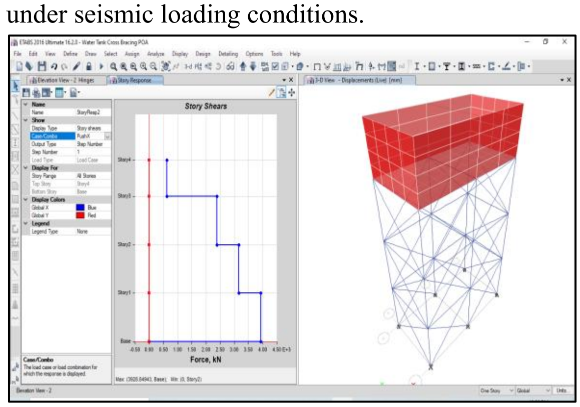


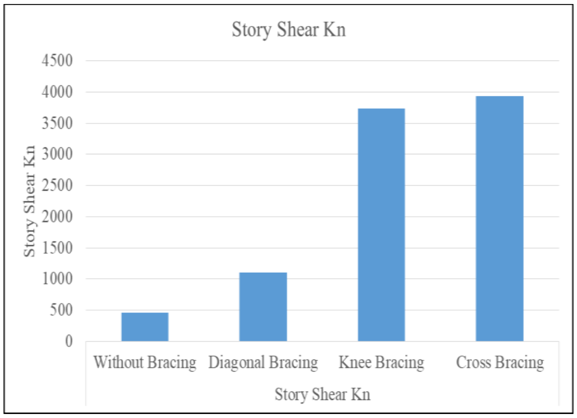
Fig 12 Story Shear Cross Brace Model

Figure 12 shows the story shear distribution for the elevated water tank with cross bracing (Model 4). The figure demonstrates the most efficient lateral force transfer among all models, with significantly reduced shear at each story level, confirming that cross bracing provides the highest stiffness and seismic resistance.

Table 3 Story Shear Kn

Story Shear Kn			
Without Bracing	Diagonal Bracing	Knee Bracing	Cross Bracing
460.87	1102.09	3737.74	3928.84

Table 3 presents the story shear values (in kN) for elevated water tank models with different bracing systems.



Graph 2 Story Shear Kn

Graph indicates that the story shear increases notably with the inclusion of bracing systems. The unbraced frame shows the lowest shear value (460.87 kN), while diagonal bracing improves it to 1102.09 kN. Knee bracing (3737.74 kN) and cross bracing (3928.84 kN) exhibit the highest shear capacities, signifying superior lateral load resistance and overall structural stability.

VII. CONCLUSION

The present study aimed to evaluate and optimize the structural performance and stability of elevated water tank frames using various bracing configurations, namely unbraced, diagonal, knee, and cross bracing. The analysis was carried out using finite element modeling under static and dynamic load conditions as per relevant Indian Standards. The primary focus was to understand the influence of bracing on key response parameters such as story displacement, spectral displacement, story shear, and overall lateral stiffness Comparison of all models revealed that cross bracing provided the best balance between strength and stiffness, ensuring minimal deformation and efficient energy dissipation. Diagonal bracing also showed satisfactory performance, while knee bracing offered moderate improvement over the unbraced system.

The study concludes that the type of bracing system plays a decisive role in the seismic behavior and stability of elevated water tank structures. Among the configurations analyzed, cross bracing demonstrates the highest structural efficiency, maximum stiffness, and minimum displacement, making it the most suitable bracing type for elevated water tank frames. The results emphasize that the proper selection and design of bracing can significantly enhance both the safety and economy of such essential infrastructure systems.

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