International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Comparative Study of Analysis of Elevated Water Tank Staging using Solid and Hollow RCC Columns Under Seismic Loads

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ABSTRACT
Elevated water tanks are vital for urban infrastructure, especially in flat terrains, and their structural performance during and after seismic events is of critical concern. This study presents a comparative analysis between solid and hollow square RC columns, both having the same cross-sectional area, supporting an elevated water tank with a capacity of 75,000 liters . The study investigates the effect of increased moment of inertia and stiffness in hollow columns by analysing tank response at varying staging heights (12 m, 16 m, and 20 m). The results show a reduction of 15–20% in horizontal deflection when hollow columns are used, indicating improved seismic performance without additional cost.

Keywords: Elevated , Hollow , Monolithically, Solid , Stiffness ,

1. INTRODUCTION

Elevated water tanks are critical components of municipal water supply systems, ensuring continuous water availability and enabling fire-fighting operations. However, their performance under seismic loads has often been found lacking, as evidenced by structural failures in recent earthquakes. These failures can disrupt essential services and pose public health risks.

The structural vulnerability of elevated tanks arises from their top-heavy configuration, with a significant portion of the mass elevated above the ground level. This makes the supporting columns and braces crucial for overall stability. Damage to the tank shell or support system can render the tank non-functional. Therefore, a detailed investigation into design improvements, especially under seismic conditions, is necessary.

1.1 Objective of the study

Objective of the study was to reduce material consumption and improve economy without compromising safety.

Hollow column of equivalent cross section has M.I. more compared to solid column. Stiffness of column is $12xExI/L^3$. As M.I. of the column is increases, stiffness increases and horizontal deflection reduces.

1.2 Forces on staging and design of column of water tank

The staging consist of number of columns braced together at an interval. The columns are assumed to be fixed bat brace as well as at top of tank . Therefore effective length of column is taken as distance between the bracing. [3]

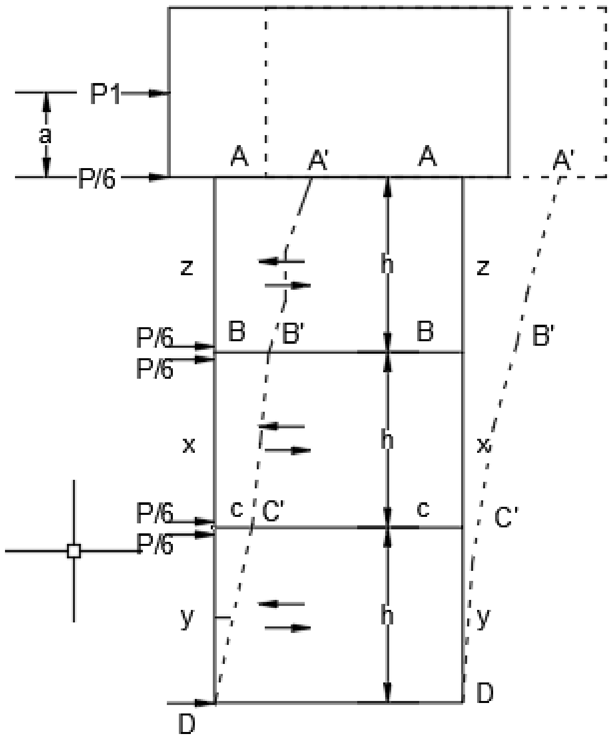


Fig. 1.1 Forces on tank supporting tower

The columns receive the vertical load of the entire tank and this load is equally divided among all columns if these are of same cross sectional area and are symmetrically placed, which usually is the case in practice. Besides this vertical load , the columns are subjected to wind or earthquake acting on the tank and tower both. These lateral forces induce bending moment, shear force and axial forces in the columns. The magnitude of these reactions depend up on the condition of fixity analysis of the tower as a space frame. It is usual to determine the reactions in the tower in conventional manner. [4]

If both ends of the columns are hinged and if the tower has no intermediate braces monolithically connected with the columns, the tower will not be stable against lateral forces and will collapse. It is therefore usual to build the columns monolithically with the tank base at top and foundation at bottom. It is also necessary to connect the columns monolithically at one or more levels with strong RCC braces. When such tower deflects under lateral forces, the columns are constrained to maintain their axes almost vertical at their top and bottom ends and also at their junctions with the braces. This happens because the tank base foundation, and braces are very stiff compared to the columns. Thus columns develop point of inflexion at the mid height of each panel. At these points, internal reactions caused in columns are only horizontal shear and vertical forces. The magnitude of these reactions can be approximately calculated by considering a tower as a whole as a single vertical cantilever beam with its section built up with columns spaced apart .If bending moments and shear forces due to lateral loads on the tower are calculated on this equivalent cantilever beam at horizontal sections passing through point of inflexion , then bending stresses in equivalent vertical cantilever beam will give vertical forces in columns and the shear stresses will give the horizontal shear force in the column at their point of inflexion.[4]

Let there be n columns in a tower (n=6 or more) located symmetrically on a circle of mean diameter D. Let sectional area of each column be "a". The total sectional area of cantilever beam is thus nxa and the section can be considered to be a ring of mean diameter D and equivalent thickness $t = nx\frac{a}{3.14xD}$ as shown in figure below. Thus the moment of inertia (I) of cantilever beam section =

$$I = 3.14xD^3x\frac{t}{8} = nxaxD^2 \div 8$$

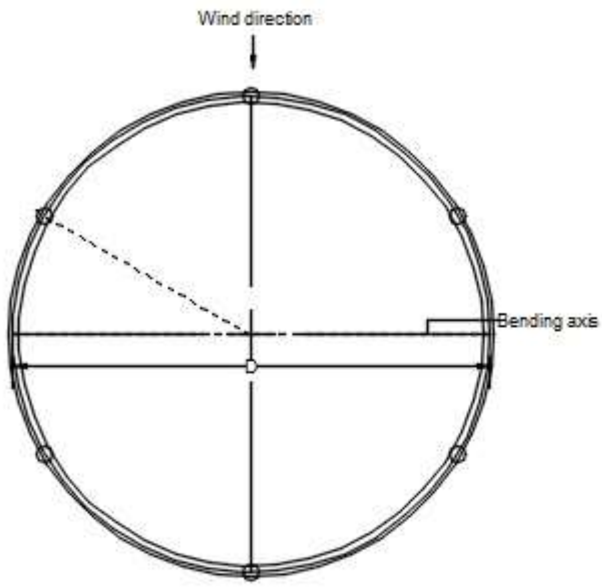


Fig. 1.2 Column of supporting tower in plan

If bending moment (M) in cantilever beam is M , the bending stress (σ b) is maximum at a point lying farthest from bending axis and is equal to

$$\frac{M}{nxax\frac{D^2}{8}} = 4xM \div (nxaxD)$$

Thus the vertical force (F) in column lying farthest on lee ward side.

$$F = 4x\frac{M}{nxaxD}xa = 4xM \div (nxD)$$

It is a thrust. Force on wind ward side farthest from bending axis is also $4xM/(nxD)$, but tensile. Vertical force in columns lying on bending axis is zero. [4]

Let the radius joining any column to axis of tower make an angle θ with the bending axis of tower .shear stress at this column=

$$q = \frac{Q}{2xtxsec\theta xnxax\frac{D^2}{8}}x2x\left(\frac{D}{2}\right)^2 \text{ x t x cos}\theta = 2\text{xQx}\cos\theta^2 \div (\text{nxa})$$

This shows that columns farthest from bending axis where θ=90 ,q is zero and it is maximum at columns lying on bending axis where θ=0. [4]

Shear force in any column is ,$SF = qxa = 2xQx\frac{cos\theta^2}{\text{nxa}}\text{xa} = 2\text{xQxcos}\theta^2 \div \text{n}$

And s max= $2xQ \div n$

It will thus seen that effect of lateral force on column of the tower is to cause only an axial forces in columns farthest from bending axis of equivalent cantilever beam and to cause only shear force at columns lying on bending axis .These forces on each column act at its point of inflexion which occurs at mid height of each panel. [4]

The shear force in column acting at the point of inflexion will cause bending moments in the column. The maximum moment will occur at the top and bottom end of each panel and will be equal to sxh÷2 , where h is the clear panel height. [4]

It will be seen that moment M and shear force Q in the equivalent cantilever beam are largest at plane passing through the points of inflexion in column in lowest panel of the tower. Thus column in this panel are subjected to largest vertical reaction and shear force due to wind. In upper panel ,these reactions go on decreasing . If total wind force on tank is P1, it can be made to act at joints as shown. Thus shear force Q at plane Y-Y $= P1 + \frac{5}{6}xP$ and the moment M about this plane

$$= \left(P1x(a + 2.5xh) + \frac{6.5}{6}\right)xPxh$$

(please refer the drawing). [4]

Total forces acting on columns of tower are-

1. Vertical load due to weight of tank, water and the columns. This will cause the axial thrust in each columns.
2. Bending moment in the columns due to wind pressure acting on the tank and columns themselves. This is critical for columns lying on bending axis of tower only.
3. Axial forces in the columns due to wind pressure acting on the tank and columns . This is critical for columns lying farthest from bending axis of the tower.
4. Shear force in columns due to wind pressure .

In practice ,the shear force is small and does not influence the design of columns. The section adopted from other considerations is always safe in shear. The section of column depends mainly on magnitude of axial force and bending moment acting on it. i. e. section is subjected to direct and bending stresses. It will be seen that direct forces due to cause (2) and (3) above add up in lee word columns and oppose each other in wind ward columns. These columns do not have moments. Columns near bending axis of tower have vertical load due to cause (1) only along with moment due to cause (2).As the wind can blow from any direction, all columns must be safe under both of above combination of forces. [4]

1.3 Weak beam-strong column concept

In framed structure horizontal and vertical members i.e. beam and slab should fail prior to vertical members , i.e. column. Beams and slab generally do not fail down even after severe damage at plastic hinge position , where as columns will rapidly collapse under vertical loading once significant spalling has taken place . Hence continuous beams on light columns are not appropriate [Fig.1.3 (c)] in earthquake prone regions, and weak beam- strong column [Fig. 1.3 (b)] arrangement should be the choice . It is very important in that it postpones complete collapse of structure. Following are the reasons for having strong columns and allowing prior yielding of beams in flexure. [5]

(a) Failure a column means the collapse of entire structure .
(b) In weak column structure, plastic deformation is concentrated in particular storey, as shown in Fig. 1. (c) and relatively large ductility factor is required .
(c) In both shear and flexure failure of column , degradations are greater than those in yielding of beams.[5]

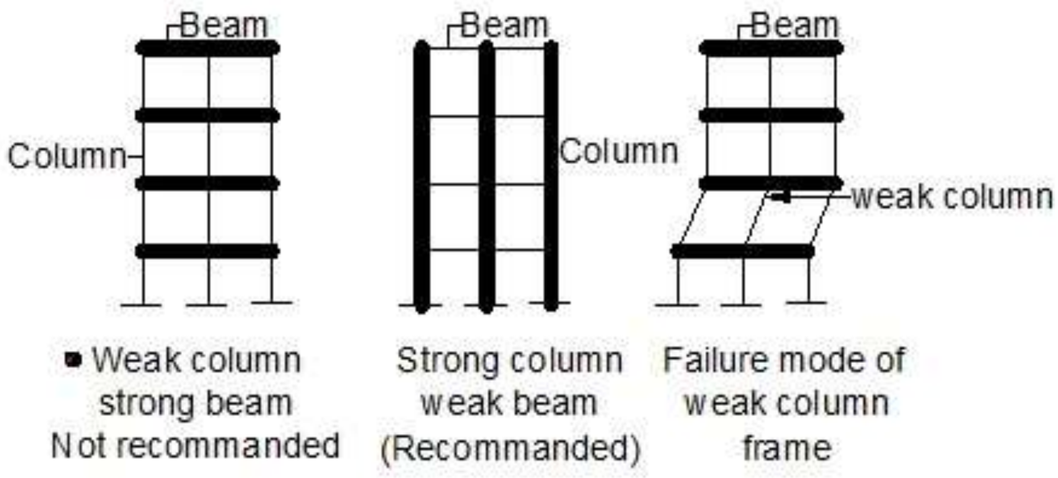


Fig. 1.3 Weak beam-strong column concept

2. LITERATURE REVIEW

Several studies have addressed the seismic behaviour of elevated water tanks, with emphasis on fluid-structure interaction, staging configuration, and design methodologies.

Omidinasab and Shakib (2011) evaluated seismic responses of RC elevated tanks and found that peak responses do not always occur at full tank condition. Around 60–70% of variations fall within one standard deviation, underlining the importance of variability in seismic inputs. However, studies focusing on **hollow column staging** remain scarce, which this research seeks to address.[1]

Mane and Angalekar (2022) studied sloshing effects in water tanks installed at intermediate floors (DOSIWAM system) and concluded that matching time periods between tank and building reduces sloshing, allowing safe integration of tanks in multi-story structures.[6]

Adil et al. (2022) analyzed different column configurations using SAP2000 and observed significant effects on base shear, time period, and moment values, highlighting the impact of structural layout on seismic behaviour.[7]

Rajesh and Sreekanth (2022) compared seismic responses using STAAD-Pro and ETABS across varying tank capacities and seismic zones. The study highlighted the influence of support type and capacity on seismic forces.[8]

Chondikar (2022) introduced carbon fibre reinforcement in overhead tank design. Time history analysis using STAAD-Pro indicated structural efficiency and potential for innovation in material usage.[9]

Djelloul and Djermane (2022) examined nonlinear behaviour of elevated steel conical tanks under seismic excitation. They found wall inclination and vertical ground acceleration significantly affect stability, requiring consideration in design.[10]

Latha (2021) compared rectangular and circular tanks, concluding that circular tanks perform better under seismic loads and are more economical for larger capacities.[11]

Anjum and Zameeruddin (2021) performed nonlinear analysis of tanks in Maharashtra and identified staging system selection as critical for minimizing seismic vulnerability.[12]

Santhosh and Sethy et al. (2020) compared IS, ACI, and BS codes, finding ACI to be the most economical while ensuring structural stability. Their study reinforced the need for code-based comparative analysis.[13]

Jani et al. (2020) assessed the impact of soil types on tank behavior. Results showed that base shear and displacement are significantly influenced by foundation conditions and staging configuration.[14]

Table: Summary of Key Literature on Seismic Analysis of Elevated Water Tanks

Author(s)	Year	Focus Area	Software/Method	Key Findings
Omidinasab & Shakib	2011	Fluid-structure interaction	Time history, ensembles	Max response ≠ full tank; seismic variability matters
Mane & Angalekar	2022	Sloshing effects, DOSIWAM system	CFD + Structural software	Proper time period match reduces sloshing; safe for reuse and installation
Adil et al.	2022	Column arrangements	SAP2000	Structural layout significantly affects seismic forces
Rajesh & Sreekanth	2022	RC frame vs. shaft structures	STAAD-Pro, ETABS	Code versions and support types impact seismic response
Chondikar	2022	Carbon fiber reinforcement	STAAD-Pro	Innovative material offers structural benefits under seismic loads
Djelloul & Djermane	2022	Inclined conical steel tanks	ANSYS	Wall inclination & vertical seismic component crucial for design
Latha M.S.	2021	Rectangular vs. circular tanks	ETABS	Circular tanks better for large capacities and seismic performance
Anjum & Zameeruddin	2021	Elevated tanks in Nanded (India)	Time history analysis	Staging system selection is critical to tank efficiency
Santhosh & Sethy et al.	2020	Codal comparison (IS, ACI, BS)	ETABS	ACI is most economical; IS and BS follow with stability
Jani et al.	2020	Soil-structure interaction	Time history analysis	Soil type significantly influences seismic forces and displacements

This review highlights a research gap in the seismic performance of **elevated tanks with hollow column staging**, which forms the core focus of the present study.

3. PROBLEM STATEMENT

This study analyzes an elevated RCC water tank with a capacity of 75,000 liters, supported on four columns (solid and hollow square sections), at staging heights of 12 m, 16 m, and 20 m. The objective is to compare the seismic performance of tanks with solid versus hollow columns of equivalent cross-sectional area.

3.1 Tank Geometry and Column Design

- **Tank Capacity**: 75 m^3 (75,000 litres)
- **Water Depth**: 3.15 m
- **Tank Area**: $= \frac{75}{3.15} = 23.81$ m^2

- **Internal Diameter (ID)**: $= \left(\frac{23.81}{0.785}\right)^{\left(\frac{1}{2}\right)} = 5.50$ m
- **Wall Thickness**: 200 mm
- **Centre-to-Centre (C/C) Tank Diameter**: 5.70 m
- **C/C Distance Between Columns**: $= \frac{5.70}{2^{\frac{1}{2}}} = 4.03\ m = 4030\ mm$

Column Section Calculations

- **Solid Column Size**: 400 mm × 400 mm
- **Cross-Sectional Area**: $= 4000 * 4000 = 160000\ mm^{\wedge}2$
- **Hollow Column Design**:
- Assume thickness = 100 mm
- Let B = outer dimension
- Equation: $B^2 - (B - 200)^2 = 160000$
- Solving yields B = 500 mm
- Final hollow column: 500 mm × 500 mm with 100 mm wall thickness

Other Design Details

- **Bracing Beam Size**: 250 mm × 350 mm
- **Footing**: Individual footings assumed
- **Concrete grade** : M30 grade
- **Steel grade** : Fe-415

3.2 Method of Analysis

The tank and supporting structure are modelled using STAAD. Pro Advanced software. Six models are analysed:

Table 3.1 Details of column size , section type

Model	Staging Height	Column Type	Column size
1	12 m	Solid	400 × 400 mm
2	12 m	Hollow	500 × 500 mm, 100 mm thick
3	16 m	Solid	400 × 400 mm
4	16 m	Hollow	500 × 500 mm, 100 mm thick
5	20 m	Solid	400 × 400 mm
6	20 m	Hollow	500 × 500 mm, 100 mm thick

Common Parameters Used

- **Foundation Depth** :- 2 m below ground level
- **Bracing Height (C/C)**: 4.0 m
- **Beam Below Tank**: 250 mm × 750 mm
- **Tank Wall Thickness**: 200 mm
- **Bottom Slab Thickness**: 250 mm
- **Roof Slab Thickness**: 150 mm

Loading Conditions

- **Self-weight**

- **Hydrostatic water pressure**
- **Live load on roof slab**
- **Seismic loads per IS code**

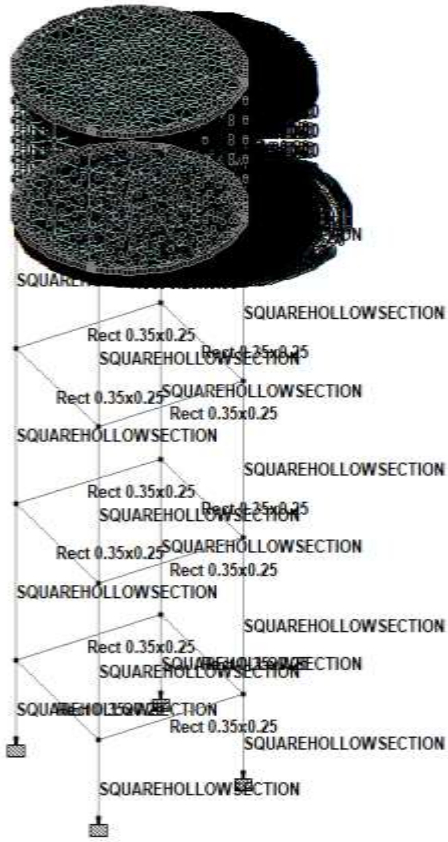


Fig. 3.1 Staad model of water tank of hollow column 12 m staging

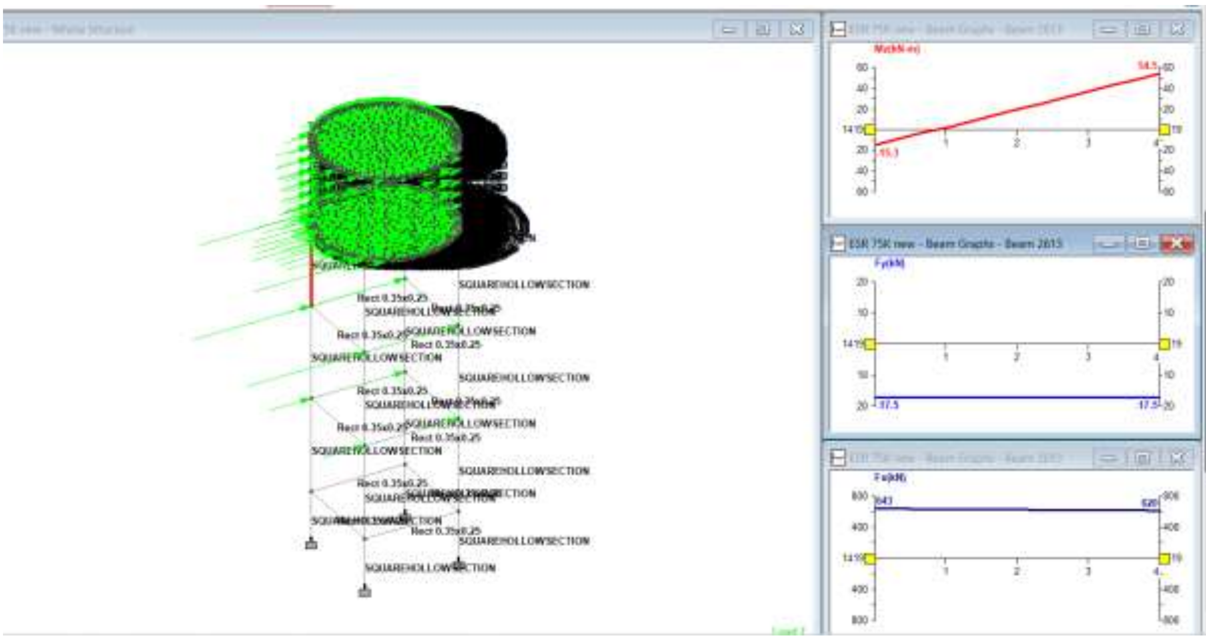


Fig. 3.2 EQ forces , BMD and SF of of water tank of hollow column 12 m staging

4-RESULTS AND DISCUSSION

Comparative Structural Performance Analysis

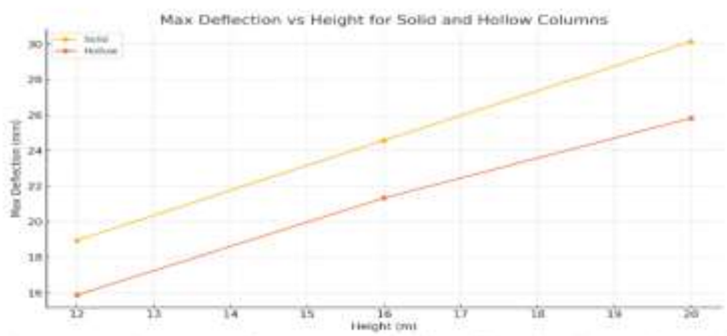
The objective of this analysis is to evaluate the seismic performance of ESRs supported on solid and hollow RCC columns under identical loading and geometric configurations. Key parameters assessed include maximum deflection, bending moments, shear forces, footing reactions, and bending stresses.

4.1 Maximum Deflection (in mm)

Table 4.1 Abstract of max. deflection

Model	Column Type	Staging Height	Max. Deflection
1	Solid	12 m	18.94 mm
2	Hollow	12 m	15.88 mm
3	Solid	16 m	24.58 mm
4	Hollow	16 m	21.33 mm
5	Solid	20 m	30.14 mm
6	Hollow	20 m	26.76 mm

Solid columns show higher deflections across all heights.



Here's a sample chart comparing **Max Deflection** vs **Height** for Solid and Hollow columns. This gives a clear visual distinction between the two types.

Fig. 4.1 Comparison of max deflection v/s height of solid and hollow column

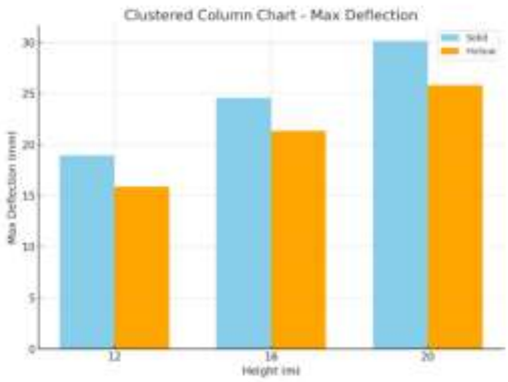


Fig. 4.2 Staging height wise Comparison of max deflection v/s height of solid and hollow column

- **Inference**: Hollow columns provide increased lateral stiffness, reducing displacement under seismic loading.

4.2 Maximum Bending Moments (My and Mz)

Table 4.2 Abstract of max. bending moments

Model	My (N·m)	Mz (N·m)
Solid Columns	36.73	32.21
Hollow Columns	62.39	54.55

Hollow columns exhibit greater moment values, especially in Mz.

- My increases from 36.73 N-m (solid) to 62.39 N-m (hollow)
- Mz increases from 32.21 kN-m (solid) to 54.55 kN-m (hollow)

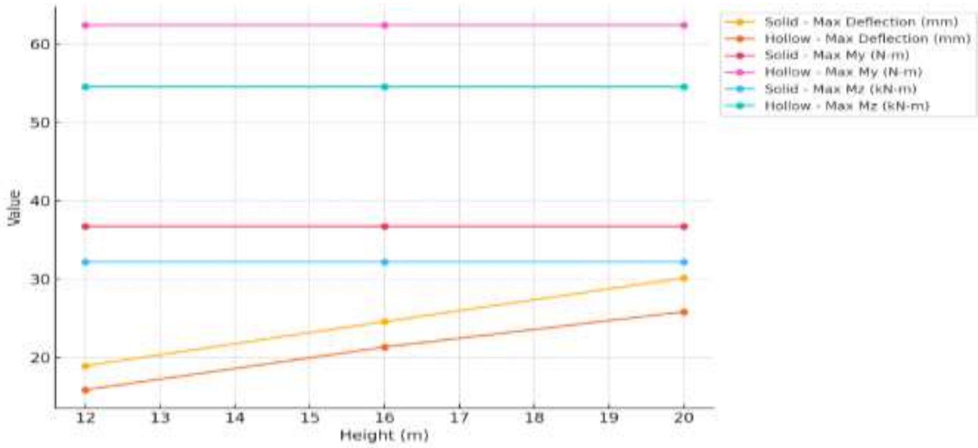


Fig. 4.3 Line chart showing structural parameters

- **Inference**: Due to increased section modulus and reduced self-weight, hollow columns endure higher bending moments.

4.3. Maximum Shear Forces (Fy and Fz)

- Similar trend observed as in moments.
  - Shear in Fy increases from 10.69 kN (solid) to 17.47 kN (hollow)
  - Shear in Fz increases from 12.15 kN to 19.94 kN

- **Inference**: Hollow sections attract more shear due to higher stiffness, but remain within safe design limits.

4.4. Reaction at Footing

- Increases with staging height, with no major difference between solid and hollow columns.
  - At 12 m: ~736.5 kN for both
  - At 20 m: ~806.8 kN
- **Inference**: Base reaction is primarily governed by tank weight and height; column type has negligible influence..

4.5 Bending Stresses

- Maximum positive bending stress remains consistent (~10.32 N/mm²) across all models.
- Negative bending stress is minimal and also consistent (~–2.57 to –2.59 N/mm²)
- **Inference**: Both column types maintain similar stress levels due to equivalent cross-section assumption.

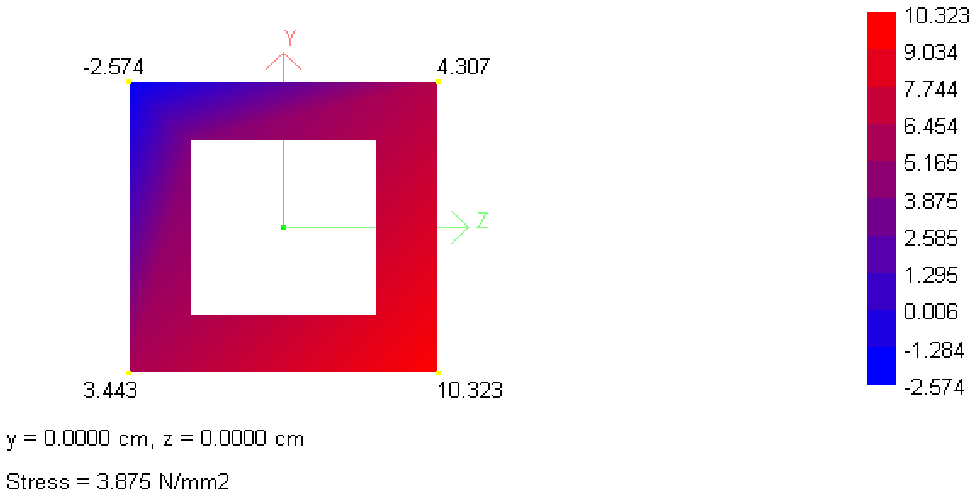


Fig. 4.4 Bending stresses in column water tank of hollow column 12 m staging

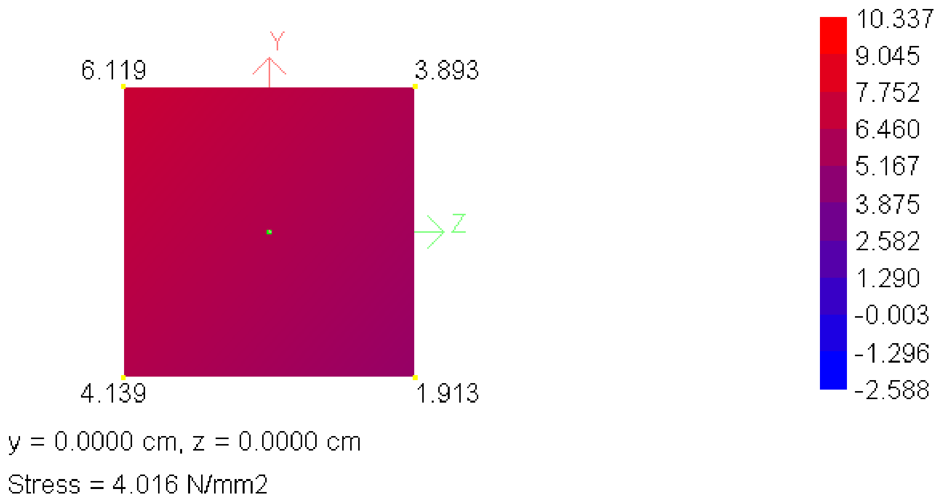


Fig. 4.5 Bending stresses in column water tank of solid column 12 m staging

- **Maximum Negative Bending Stress**: −2.57 N/mm²
- These values were found consistent for both solid and hollow column ESRs.

4.6 Summary of Results

Table 4.3 Summary of results

Height (m)	Column Type	Max Deflection (mm)	Max My (N-m)	Max Mz (kN-m)	Max Fy (kN)	Max Fz (kN)	Footing Reaction (kN)
12	Solid	18.94	36.73	32.21	10.69	12.15	736.53
12	Hollow	15.88	62.39	54.55	17.47	19.94	736.53
16	Solid	24.58	36.73	32.21	10.69	12.15	771.69
16	Hollow	21.33	62.39	54.55	17.47	19.94	771.70
20	Solid	30.14	36.73	32.21	10.69	12.15	806.82
20	Hollow	25.83	62.39	54.55	17.47	19.94	806.82

5. CONCLUSION

5.1 The moment of inertia of hollow columns (4.53×10^9 mm^4) is significantly higher than that of solid columns (2.13×10^9 mm^4) for the same cross-sectional area.

5.2 Higher stiffness of hollow columns results in reduced deflection under seismic loading, indicating improved structural performance.

5.3 Bending moments are better distributed in hollow column systems, enhancing structural integrity.

5.4 Despite these advantages, hollow-column ESRs are rarely constructed in practice, and relevant literature is limited.

5.5 This comparative analysis encourages further exploration, including dynamic and nonlinear analysis of hollow column ESR systems.

5.6 Although they attract higher internal forces, their performance remains within safe structural limits.

5.7 Adoption of hollow columns can reduce material consumption and improve economy without compromising safety.

REFERENCES

1. F. Omidinasab and H. Shakib (2011), "Seismic Response Evaluation of RC Elevated Water Tank with Fluid-Structure Interaction and Earthquake Ensemble," KSCE Journal of Civil Engineering, 16(3): 366–376.
2. Bentley , "Staad.pro advance software".
3. V.N. Vazirani and M.M. Ratwani , "Design of R.C. structures", ISBN No :978-81-7409-232-8 , Khanna Publishers , 2-B , Nath market , Nai Sarak , Delhi -110006.
4. Jai krushna and O.P.Jain , "Plain and reinforced concrete vol-II", ISBN 81-85240-09-4 vol II , Nem chand and Brothers.
5. S.K. Duggal , "Earth quake resistant design of dtructures ." ISBN-13:978-0-19-568817-7 , oxford university press 2007.
6. Sneha Govindrao Mane, Dr. S. S. Angalekar "Seismic analysis of Water tank at different storey height of the Building and to check fluid sloshing effect."DOI 10.33564/IJEAST.2022
7. W. A. Adil, M. A. Baluch et.al "Effect of Different Column Arrangements on Structural Behaviour of Square Overhead Water Tank by Response Spectrum Analysis" vol 27 no.2 (2022): Technical Journal

Boggula Rajesh, G. Sreekanth "Design and analysis of different water tanks by considering slab wall and capacity in seismic zones" vol 13,issue 04, April/2022. ISSSN No 0377-9254

8. Krushnarth Chondikar "Design of Overhead Tank with Carbon Fibre/Fibre Rebar as Reinforcement and Time History Analysis using STAAD-Pro software."IRJET, vol :09 Issue:04- 2022
9. Nasser Dine Hadj Djelloul, Mohamed Djermane "Non-linear numerical study of the dynamic response of elevated steel conical tank under seismic excitation" DOI:10.37789/rjce.2022.13.3.5
10. LathaM.S."Comparison of analysis between Rectangular and Circular overhead water tank" DOI:10.32722/arcee.v2i02.3636 ,2021
11. Tayyaba Anjum, Mohd. Zameeruddin "Evaluation of Efficiency of the Elevated Water Tank Under the Seismic Loads"IJCE journal vol 8 issue 1 (2021)
12. Vangaveti Sai Santhosh, Susanta Kumar Sethy et.al "Seismic Analysis of Overhead Water Tank Using Indian, American and British Codal Provisions" IRJET vol 7 issue 5, may-2020
13. Bhakti B. Jani et.al "Effects of Soil Condition on Elevated Water Tank Using Time History Analysis with Different Staging Systems" DOI:10.14445/23488352/IJCE-v716P105 (2020)