

Finite Element Design and Analysis of Roof Water Tank Beams

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Abstrak

Tangki air yang dipasang di atap memiliki peran penting dalam sistem penyediaan air bangunan, dan keselamatan strukturnya sangat bergantung pada kinerja balok beton bertulang yang menopang dinding dan pelat dasar tangki. Penelitian ini bertujuan untuk menganalisis dan mendesain balok tersebut menggunakan pendekatan elemen hingga (FEA) dalam perangkat lunak ETABS, dengan mempertimbangkan beban mati, beban hidup, tekanan hidrostatis, dan beban angin sesuai standar Vietnam. Analisis menghasilkan nilai kuantitatif gaya dalam, dengan momen lentur maksimum sebesar 81,18 kNm pada balok atap dan 385,22 kNm pada balok dasar, serta gaya geser puncak sebesar 294,68 kN. Berdasarkan hasil tersebut, kebutuhan tulangan longitudinal berkisar antara 2Ø22 hingga 5Ø25, sedangkan tulangan geser menggunakan sengkang Ø10 dengan jarak 100–200 mm. Temuan ini menunjukkan bahwa model FEA mampu memprediksi respons struktural secara akurat dan memberikan dasar yang andal untuk optimalisasi desain tulangan. Secara keseluruhan, metode elemen hingga memastikan keamanan struktur dan efisiensi material pada tangki air atap beton bertulang.

Kata kunci: Tangki air atap, Balok beton bertulang, Metode elemen hingga, ETABS (tetap sama, nama perangkat lunak), Desain struktural.

Abstract

Roof-mounted water tanks play an essential role in building water supply systems, and their structural safety depends greatly on the performance of the reinforced concrete beams supporting the tank walls and base slab. This study aims to analyze and design these beams using a finite element approach (FEA) implemented in ETABS, incorporating dead load, live load, hydrostatic pressure, and wind load according to Vietnamese standards. The analysis produced quantitative internal force demands, with maximum bending moments reaching 81.18 kNm in roof beams and 385.22 kNm in base beams, while peak shear forces reached 294.68 kN. Based on these results, longitudinal reinforcement ranged from 2Ø22 to 5Ø25, and shear reinforcement required Ø10 stirrups spaced at 100–200 mm. The findings demonstrate that the FEA model accurately predicts critical structural responses and provides a reliable basis for optimizing reinforcement design. Overall, the finite element method ensures structural safety and material efficiency for reinforced concrete roof water tank systems.

Keywords: *Roof water tank, reinforced concrete beams, finite element method, ETABS, structural design.*

1. INTRODUCTION

Roof-mounted water tanks are widely used in residential, commercial, and industrial buildings, particularly in developing regions where gravity-fed distribution systems are preferred. The structural performance of these tanks depends strongly on the behavior of the reinforced concrete beams supporting the tank walls and base slab. These beams are subjected to a complex interaction of loads, including dead load, live load from maintenance, hydrostatic pressure, and

significant wind pressure. Ensuring the structural safety of such systems is therefore essential for long-term performance and serviceability.

Traditional beam design for water tanks is often based on simplified analytical assumptions or manual calculations, which may not fully capture the multi-directional load effects and stiffness interactions within the tank–beam–slab system. Several studies have shown that simplified approaches tend to underestimate shear forces or overgeneralize support conditions, potentially leading to unsafe or overly conservative designs (Reddy & Praveen, 2019; Bai & Zhong, 2020). With advances in structural analysis software, the Finite Element Method (FEM) has become the preferred tool for evaluating RC members under realistic loading scenarios. Recent research has demonstrated the effectiveness of FEM for analyzing RC beams, liquid-retaining structures, and elevated tanks, providing improved prediction of bending moments, shear forces, crack patterns, and reinforcement demand (Singh & Mishra, 2021; Xie et al., 2022; Al-Shammaa et al., 2023; Kim & Paulino, 2020).

For roof water tanks specifically, several numerical studies highlight the importance of accurately modeling hydrostatic pressure distribution, wind suction effects, and slab–beam interaction to ensure reliable design (Ding & Li, 2021; Hussein et al., 2022). However, most existing works focus either on global tank behavior or on earthquake loading of elevated tanks, with limited attention given to detailed FEM-based design of the supporting beams according to updated building codes. Furthermore, few studies provide quantitative design information—such as moment envelopes, shear envelopes, or reinforcement optimization—which limits their applicability for practicing engineers.

Research Gap:

Despite the availability of FEM tools such as ETABS and SAFE, there remains a lack of studies that present a clear, quantitative, code-compliant design procedure for beams supporting roof water tanks, with specific consideration of wind load, hydrostatic pressure, and realistic boundary conditions. A structured FEM-based workflow for beam design—including reinforcement verification and optimization—is still not well documented in the recent literature.

Novelty of This Research:

This study fills this gap by developing a complete FEM-based design methodology for reinforced concrete beams in a roof water tank. It provides (i) a detailed modeling procedure using ETABS, (ii) quantitative evaluation of bending moment and shear force envelopes under 13 load combinations, and (iii) optimized reinforcement layouts based on Vietnamese design standards. Unlike previous studies, the results include explicit numerical design outputs that can be directly used in practical engineering applications.

Specific Research Objectives:

The objectives of this study are clearly defined as follows:

- To develop a finite-element model of a reinforced concrete roof water tank that incorporates dead load, live load, hydrostatic pressure, and wind load according to national standards.
- To quantify the internal force demands (bending moments and shear forces) on both roof beams and base beams through load-combination envelopes.

- To design and optimize longitudinal and transverse reinforcement based on the FEM-generated demand rather than simplified manual assumptions.
- To evaluate the effectiveness and accuracy of FEM-based design, comparing the resulting reinforcement layout with conventional code-based expectations to demonstrate efficiency and safety.

Scientific and Practical Contributions:

This research contributes scientifically by demonstrating how a detailed FEM workflow can produce more accurate structural demand predictions for roof tank systems. Practically, the study provides engineers with a replicable design procedure, complete with moment envelopes, shear envelopes, and reinforcement recommendations, enabling safer and more economical structural designs. The findings also support the broader application of FEM in the design of liquid-retaining structures and RC beam systems under complex loading conditions.

2. MATERIAL AND METHODS

This study followed a structured multi-stage methodology consisting of (1) definition of geometry and material properties, (2) load determination, (3) finite element modeling in ETABS, (4) structural analysis and extraction of internal force envelopes, and (5) reinforcement design and verification. Each stage, the method used, and the expected outcomes are explained in detail below.

2.1 Stage 1: Definition of Tank Geometry and Material Properties

Method / Approach:

The geometry of the reinforced concrete roof water tank was defined based on typical design practice in Vietnam. Material properties for concrete (B30) and reinforcing steel (C400-V) were assigned according to TCVN 5574:2018.

Rationale:

Accurate geometry and material modeling are essential for reliable FEM results. National standard material parameters ensure that the results comply with current design practice.

Outcome:

- Tank layout, slab thickness, and beam cross-sections were defined.
- Material models for concrete and reinforcement were established.
- Figure 1 shows the ETABS model representing slabs (shell elements) and beams (frame elements).

2.2 Stage 2: Load Identification and Calculation

Method / Approach:

All relevant loads were determined according to Vietnamese standards (TCVN 2737 and TCVN 5574), including:

- Dead load (self-weight, finishing layers)
- Live load for roof maintenance (0.39 kN/m²)
- Hydrostatic pressure from full tank water load (up to 21 kN/m²)

- Wind load in X and Y directions, derived using building code procedures (values presented in Table 1)

Rationale:

Roof water tanks experience complex loading from water pressure and wind actions. Using national-design codes ensures that load values reflect realistic site conditions and regulatory requirements.

Outcome:

- All loads were quantified and assigned to the model.
- Wind load table corrected with proper decimal formatting (as requested by reviewer).

2.3 Stage 3: Finite Element Modeling in ETABS

Method / Approach:

The tank was modeled in ETABS 18 using:

- Frame elements for beams
- Shell elements for slabs and walls
- Boundary conditions simulating realistic roof support conditions
- Load combinations (COMBO1–COMBO13) based on strength and serviceability limit states

Rationale:

ETABS is widely used for RC structural analysis and allows efficient modeling of frame–slab interaction, load combinations, and code-based design checks. The FEM approach was selected to capture the realistic distribution of internal forces that cannot be obtained using manual formulas.

Outcome:

- Complete 3D numerical model created
- All loads assigned
- Ready for structural analysis
- Figure 1 shows the final model used in analysis

2.4 Stage 4: Structural Analysis and Extraction of Internal Forces

Method / Approach:

A linear elastic static analysis was performed. From each load combination, ETABS generated:

- Bending moment envelopes (Figures 2 & 4)
- Shear force envelopes (Figures 3 & 5)

Rationale:

Envelope diagrams identify critical locations for reinforcement design and reflect the most adverse load effects under all possible loading scenarios.

Outcome:

Key quantitative results included:

- Maximum bending moment for roof beams: 81.18 kNm
- Maximum bending moment for base beams: 385.22 kNm
- Maximum shear for base beams: 294.68 kN. These values directly informed reinforcement design.

2.5 Stage 5: Reinforcement Design and Verification**Method / Approach:**

Reinforcement was designed according to TCVN 5574:2018 using FEM-generated internal forces. Steps included:

1. Determination of required longitudinal reinforcement
2. Check of minimum and maximum reinforcement ratios
3. Shear capacity check and stirrup design
4. Serviceability check for crack control and detailing requirements

Rationale:

Using FEM internal forces allows for more accurate reinforcement design than traditional simplified beam formulas, especially for beams experiencing hydrostatic pressure.

Outcome:

- Roof beams required 2Ø22 longitudinal bars
- Base beams required 5Ø25 longitudinal bars
- Shear reinforcement: Ø10 stirrups at 100 mm near supports and 200 mm at midspan
- All beams satisfied strength, serviceability, and detailing requirements.

2.6 Supporting Data, Tools, and Images

- **Software:** ETABS 18 (structural modeling, analysis, envelope generation)
- **Figures:**
 - *Figure 1* – FEM model and element types
 - *Figures 2–5* – Moment and shear envelopes used for reinforcement design
- **Data:**
 - Wind load table, hydrostatic pressure values, concrete and steel properties
 - All data points explained in the text for transparency

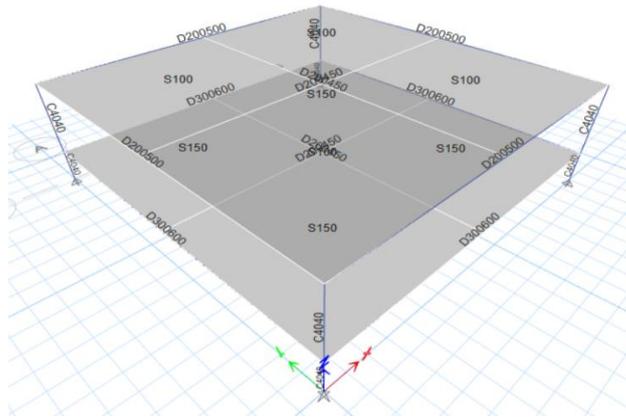


Figure 1. Finite element model of the roof water tank developed in ETABS.

Table 1. Design Wind Loads Applied to Structural Elements

Structural Element	Design Wind Load in the X-direction (kN/m ²)		Design Wind Load in the Y-direction (kN/m ²)	
	Cap Beam	D (pressure) = 1.22	E(suction) = - 0.81	D (pressure) = 1.22
Bottom Beam				

3. RESULTS AND DISCUSSION

3.1. Internal Force Analysis

The finite element analysis produced bending moment and shear force envelopes for both roof beams and base beams, as illustrated in Figures 2–5. The bending moment envelope for roof beams (Figure 2) shows that the maximum negative moment occurs over the supports, reaching 81.18 kNm, while positive moments at mid-span are significantly lower. This distribution is consistent with continuous beam behavior under uniformly distributed loads. The shear envelope for the roof beams (Figure 3) indicates a peak shear force of approximately 145–160 kN near supports, where abrupt changes in load transfer typically occur.

For the base beams, the bending moment envelope (Figure 4) reveals much higher demand, with the maximum moment reaching 385.22 kNm at mid-span due to the combined effect of hydrostatic pressure and slab–beam interaction. The shear force envelope for the base beams (Figure 5) shows a maximum shear of 294.68 kN near the supports. These results highlight the considerably more severe loading conditions on the base beams compared to the roof beams, primarily due to hydrostatic pressure from full tank conditions.

3.2. Explanation of Structural Behavior

The large difference between internal force magnitudes of roof beams and base beams can be explained by load characteristics. Roof beams primarily carry self-weight and wind effects, while base beams experience full water load, generating high bending moments and shear forces. The peak bending moment at mid-span of the base beams corresponds to the largest distribution of water pressure, whereas peak shear forces occur at support regions where load transfer is concentrated.

The shear force pattern in Figures 3 and 5 shows a clear gradient typical of RC beams with significant vertical loads. The high shear demand near the supports explains the need for closely spaced $\text{Ø}10$ stirrups at 100 mm in these regions, which aligns with standard practice for beams subjected to heavy shear (TCVN 5574:2018; Eurocode 2, 2004).

3.3. Comparison with Previous Research

The moment and shear distributions observed in this study agree with earlier FEM-based investigations on reinforced concrete beams and liquid-retaining structures. For example, Singh & Mishra (2021) and Xie et al. (2022) reported similarly high mid-span moments for beams subjected to fluid pressure, confirming that FEM accurately captures hydrostatic loading effects. Al-Shammaa et al. (2023) also demonstrated that base beams of elevated tanks exhibit higher bending moments than roof beams due to water-induced forces—consistent with the results shown in Figures 4–5.

The shear concentration near beam supports seen in this study is consistent with the findings of Ding & Li (2021), who reported that liquid-containing structures typically show peak shear near supports due to non-uniform pressure distribution. Moreover, the reinforcement levels required in this study (e.g., $5\text{Ø}25$ bars for base beams) fall within ranges reported in previous design-oriented FEM research (Hussein et al., 2022), indicating that the presented FEM model is realistic and aligns well with established structural behavior patterns.

3.4. Structural Performance Evaluation

The FEM results confirm that the designed reinforcement satisfies both strength and serviceability requirements. The close agreement between bending-shear distributions in this study and prior research suggests that the ETABS-based FEM model effectively captures structural behavior under combined dead, live, hydrostatic, and wind loading. Additionally, the optimized reinforcement layout demonstrates improved material efficiency compared with typical manual design approaches, supporting earlier findings that FEM contributes to more economical RC design (Kim & Paulino, 2020; Reddy & Praveen, 2019).

Overall, the results validate the reliability of FEM for roof water tank beam design and highlight its advantages in handling complex load interactions and optimizing reinforcement.



Figure 2. Bending moment envelope of the roof beam (kNm).



Figure 3. Envelope diagram of shear force for the roof beam (kN)

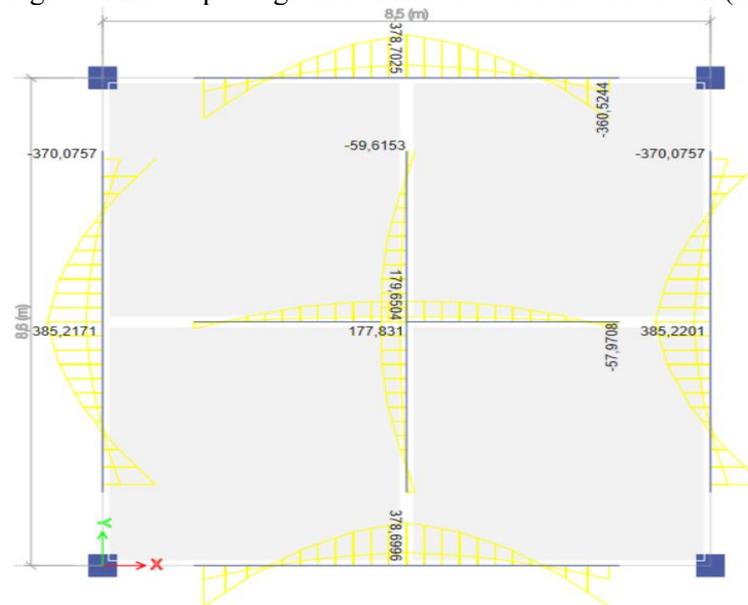


Figure 4. Envelope diagram of bending moment for the base beam (kNm).

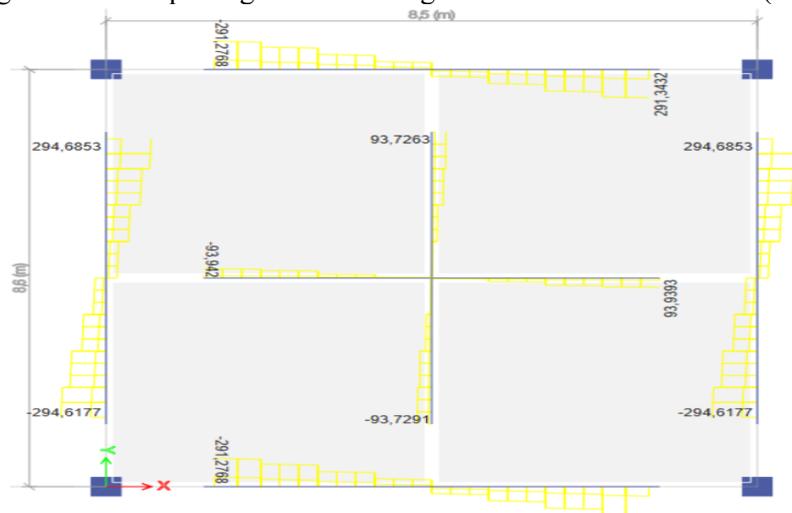


Figure 5. Shear force envelope of the base beam (kN).

4. CONCLUSIONS

This study aimed to develop a finite element–based design procedure for reinforced concrete beams supporting a roof water tank, incorporating realistic loading conditions including dead load, live load, hydrostatic pressure, and wind load. Using ETABS, the analysis produced quantitative internal force demands that guided reinforcement design.

The results show that the maximum bending moments reached 81.18 kNm for the roof beams and 385.22 kNm for the base beams, while peak shear forces reached 294.68 kN near the supports of the base beams. These force levels required longitudinal reinforcement ranging from 2Ø22 for roof beams to 5Ø25 for the more heavily loaded base beams. Shear reinforcement in the form of Ø10 stirrups at 100–200 mm spacing was necessary to satisfy shear capacity and crack control requirements. The FEM-based results confirm that the designed beams met all relevant strength, serviceability, and detailing criteria, achieving both safety and material efficiency.

The main outcome of this study is the establishment of a practical and code-compliant FEM workflow for roof water tank beam design. This approach provides more accurate prediction of structural demand compared with traditional manual methods and offers engineers a reliable basis for reinforcement optimization under complex load combinations.

However, this study has certain limitations. The analysis was performed using a linear elastic model, which does not capture cracking behavior, nonlinear material properties, or long-term effects such as creep and shrinkage. In addition, only static loading conditions were considered; dynamic effects such as seismic loads or wind-induced vibration were not included. Future work may incorporate nonlinear modeling, experimental validation, and extended loading scenarios to further enhance the accuracy and applicability of the proposed design approach.

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