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Finite Element Analysis of Reinforced Concrete Frame Structures for Safe and Inclusive Educational Facilities Using ETABS

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ABSTRACT

This study analyzes a reinforced concrete frame axis of a multi-story educational building using the Finite Element Method and ETABS software. The analysis applied Vietnamese standards (TCVN 2737:2023, TCVN 5574:2018, and TCVN 9386:2012) to evaluate dead loads, live loads, wind loads, seismic loads, internal forces, displacement, and reinforcement requirements. The designed beams and columns satisfied strength and serviceability criteria, including horizontal displacement limits. In the context of inclusive education, structurally safe buildings are essential for protecting all learners, including students with special needs who may require stable, accessible, and secure learning environments. This study provides an engineering-based reference for designing safer and more inclusive educational facilities.

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1. INTRODUCTION

The development of safe and reliable educational buildings is an important part of creating inclusive learning environments. Educational facilities must provide not only functional classrooms but also safe, stable, and accessible spaces for all learners. In special needs education, building design is often associated with accessibility, circulation, ramps, assistive facilities, and inclusive spatial planning. However, structural safety is also fundamental because students with special needs may require more time, support, and environmental stability during daily learning activities or emergencies. Previous work on the design of worship places for people with special needs shows that inclusive spatial planning must consider accessibility, safety, and user needs in built environments (Kurniawan, 2022).

From an engineering perspective, safe educational facilities require structural systems that can resist dead loads, live loads, wind loads, and seismic loads. A structurally unsafe building can create serious risks for all users, especially children, students with disabilities, teachers, and school personnel who depend on predictable and secure learning spaces. Therefore, the structural design of educational buildings should be understood as part of inclusive infrastructure. When buildings are designed to meet strength and serviceability requirements, they contribute to safer learning participation and support the broader goals of inclusive education. The Finite Element Method (FEM) is widely used in structural engineering because it allows engineers to analyze complex building behavior under multiple load conditions. FEM-based modeling can be used to calculate internal forces, displacement, drift, and reinforcement requirements in reinforced concrete structures.

Based on previous studies on FEM and XFEM applications in analyzing arbitrary openings, functionally graded plates, stress concentration, strain energy release rate, stress intensity factors, crack propagation, dynamic response, and nonlinear structural behavior (Nguyen, 2025a; Nguyen, 2025b; Nguyen, 2025c; Nguyen, 2025d; Nguyen, 2025e; Nguyen, 2025f; Nguyen, 2025g; Nguyen, 2025h; Nguyen, 2025i; Nguyen and Huang, 2021; Nguyen and Huang, 2022a; Nguyen and Huang, 2022b; Nguyen and Huang, 2023; Nguyen and Huang, 2025), this study applies FEM-based ETABS modeling to analyze a reinforced concrete frame structure and relate structural safety to the development of safe and inclusive educational facilities. In this study, ETABS was used as the main computational tool for modeling the reinforced concrete frame, applying load combinations, and evaluating the structural performance of Frame Axis 2. This approach is consistent with established finite element applications for structural analysis and reinforced concrete design. This study used Vietnamese national standards to guide structural loading, reinforced concrete design, and seismic analysis, namely TCVN 2737:2023 for loads and actions, TCVN 5574:2018 for reinforced concrete structures, and TCVN 9386:2012 for seismic design of buildings. These standards provide the basis for determining load effects, material resistance, structural safety, and serviceability requirements in the Vietnamese context. Therefore, this study aims to analyze the reinforced concrete frame axis of a multi-story educational building using ETABS and to discuss how structural safety can contribute to safe and inclusive educational facilities. Dead and live loads are considered according to TCVN 2737:2023, reinforced concrete members are designed according to TCVN 5574:2018, and seismic analysis follows TCVN 9386:2012. These standards provide the basis for determining load effects, material resistance, structural safety, and serviceability requirements in the Vietnamese context. Although the paper focuses on structural analysis, its relevance to AJCSNE lies in the relationship between building safety and inclusive educational participation. Safe educational infrastructure supports all learners, including students with special needs who may face additional barriers during movement, evacuation, and access to classroom spaces.

2. METHOD

This study used a finite element structural analysis and design approach to evaluate the performance of Frame Axis 2 in a multi-story educational building. The structure was modeled and analyzed using ETABS to determine internal forces, displacement, drift, and reinforcement requirements for beams and columns. This approach was used to verify whether the reinforced concrete frame satisfied strength and serviceability criteria while supporting safe educational facility design.

The analysis followed Vietnamese national standards. Dead and live loads were determined based on TCVN 2737:2023, reinforced concrete design followed TCVN 5574:2018, and seismic analysis followed TCVN 9386:2012. The structural materials consisted of B30 concrete, CB400-V steel for longitudinal reinforcement, and CB300-T steel for stirrups.

The ETABS model was developed as a reinforced concrete frame system with fixed supports at the foundation. The analysis considered dead load, live load, wind load, and seismic load. Wind load was determined for Region II.C, Ho Chi Minh City, while seismic load was evaluated using the response spectrum method. Load combinations were applied based on ultimate and serviceability limit states.

After analysis, bending moments, shear forces, axial forces, horizontal displacement, and inter-story drift were extracted from the ETABS output. Horizontal displacement was checked using the serviceability limit $\Delta \leq h/500$, where Δ is the maximum horizontal displacement and h is the building height. Beam reinforcement was designed based on maximum bending moment and shear force, while column reinforcement was designed under axial load and biaxial bending. The final interpretation examined whether the frame met structural safety requirements and how reliable structural design can support safe and inclusive educational facilities.

3. RESULTS AND DISCUSSION

3.1. ETABS Structural Model and Frame Axis Configuration

The reinforced concrete building was modeled using ETABS to evaluate the structural response of Frame Axis 2 under multiple loading conditions. The model represented the main beams, columns, supports, and story levels of the building. This modeling process was important because finite element analysis enables evaluation of structural behavior before construction, including internal forces, deformations, drift, and reinforcement demands. **Figure 1** shows the structural model developed in ETABS. The building was modeled as a multi-story reinforced concrete frame system. The model allowed the structure to be analyzed under vertical and lateral loads. For educational facilities, such modeling is important because structural safety is a basic requirement for protecting all building users, including students with special needs who may require stable, accessible, and predictable learning environments.

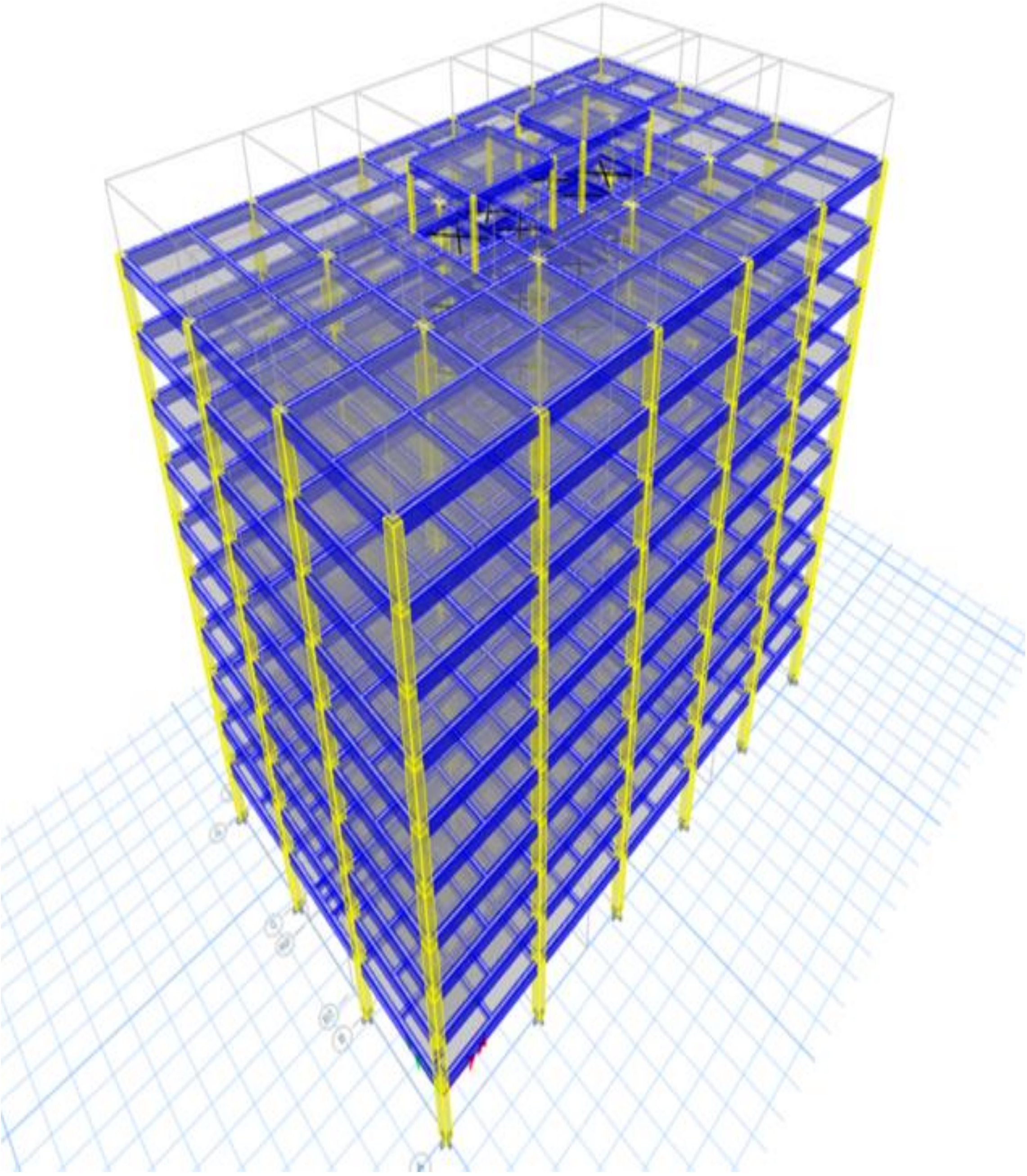


Figure 1. Structural model.

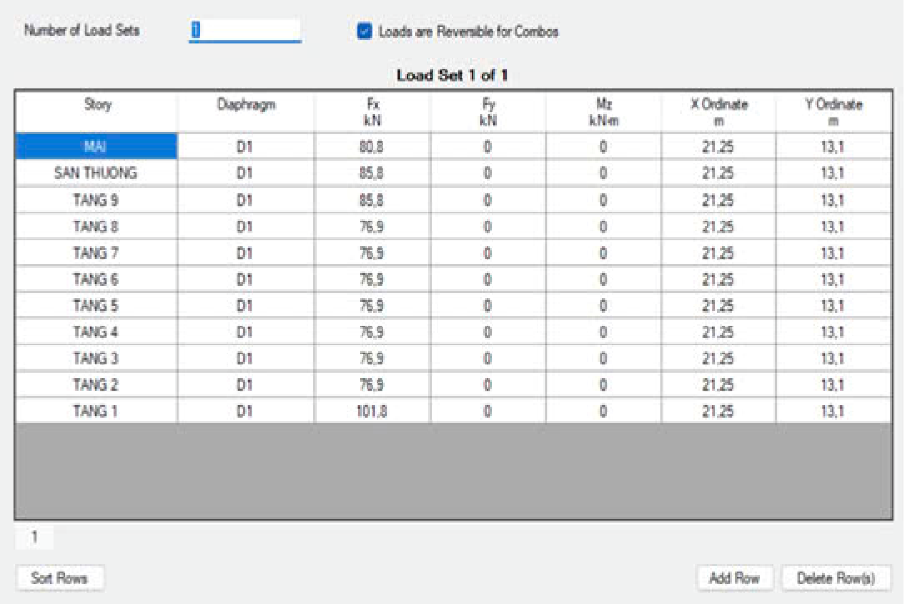
Figure 2 shows the selected frame axis used for detailed analysis. Frame Axis 2 was used to examine the distribution of internal forces and structural response under load combinations. This frame-based analysis is useful because beams and columns are the main structural members responsible for carrying gravity and lateral loads in reinforced concrete buildings.

Figure 2. Calculation diagram of Frame Axis 2 in ETABS.

3.2. Load Assignment and Structural Response

The structure was analyzed under dead load, live load, wind load, and seismic load according to Vietnamese design standards. Dead and live loads were based on TCVN 2737:2023. Reinforced concrete design followed TCVN 5574:2018, while seismic considerations followed TCVN 9386:2012. These standards provided the basis for checking both strength and serviceability.

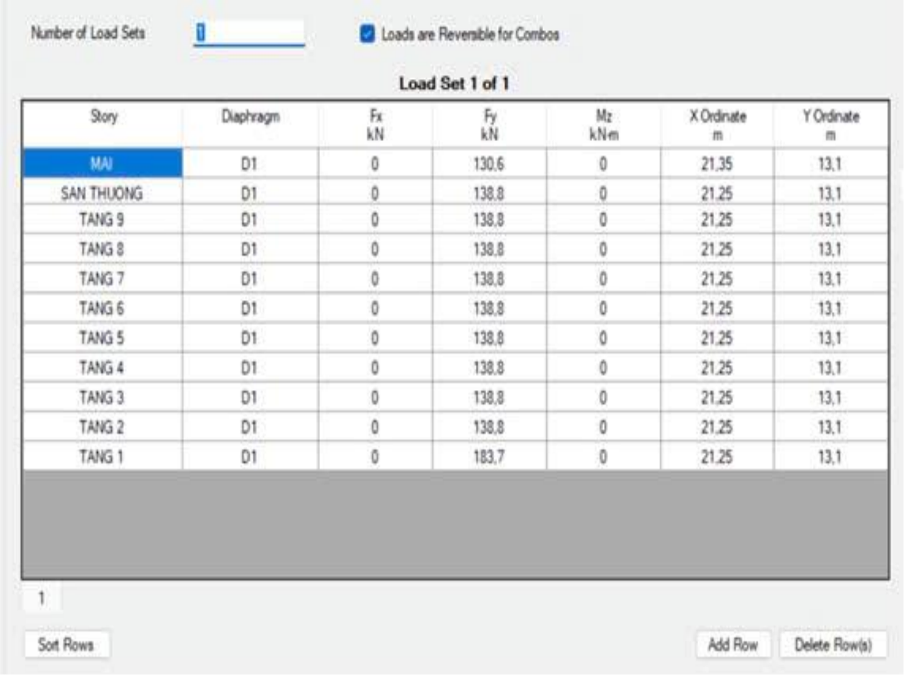
Wind load was assigned in both X and Y directions because lateral forces can affect the stability and drift performance of high-rise reinforced concrete frames. **Figures 3 and 4** show the wind load assignments used in the ETABS model. Wind loads were applied to represent lateral actions on the building. The assignment of wind load in both directions was necessary to evaluate how the frame responds to horizontal forces. This is important for serviceability because excessive lateral displacement can affect building comfort, safety, and non-structural elements. In the context of inclusive educational buildings, controlling lateral movement is also important because users with mobility limitations or sensory sensitivities may be more affected by uncomfortable or unsafe building conditions.



Load Set 1 of 1

Story	Diaphragm	Fx kN	Fy kN	Mz kN-m	X Ordinate m	Y Ordinate m
MAI	D1	80,8	0	0	21,25	13,1
SAN THUONG	D1	85,8	0	0	21,25	13,1
TANG 9	D1	85,8	0	0	21,25	13,1
TANG 8	D1	76,9	0	0	21,25	13,1
TANG 7	D1	76,9	0	0	21,25	13,1
TANG 6	D1	76,9	0	0	21,25	13,1
TANG 5	D1	76,9	0	0	21,25	13,1
TANG 4	D1	76,9	0	0	21,25	13,1
TANG 3	D1	76,9	0	0	21,25	13,1
TANG 2	D1	76,9	0	0	21,25	13,1
TANG 1	D1	101,8	0	0	21,25	13,1

Figure 3. Wind Load X Assignment.



Load Set 1 of 1

Story	Diaphragm	Fx kN	Fy kN	Mz kN-m	X Ordinate m	Y Ordinate m
MAI	D1	0	130,6	0	21,35	13,1
SAN THUONG	D1	0	138,8	0	21,25	13,1
TANG 9	D1	0	138,8	0	21,25	13,1
TANG 8	D1	0	138,8	0	21,25	13,1
TANG 7	D1	0	138,8	0	21,25	13,1
TANG 6	D1	0	138,8	0	21,25	13,1
TANG 5	D1	0	138,8	0	21,25	13,1
TANG 4	D1	0	138,8	0	21,25	13,1
TANG 3	D1	0	138,8	0	21,25	13,1
TANG 2	D1	0	138,8	0	21,25	13,1
TANG 1	D1	0	183,7	0	21,25	13,1

Figure 4. Wind Load Y Assignment.

The finite element analysis was then performed using several load combinations. The frame was subjected to combinations that included gravity loads, wind effects, and seismic effects. Internal forces, including bending moments, shear forces, and axial forces, were extracted from the ETABS output. The results were used as the basis for beam and column reinforcement design.

3.3. Moment and shear force analysis

The analysis produced moment and shear envelope diagrams for Frame Axis 2. These diagrams were used to identify critical sections in beams and columns and to determine the required reinforcement. **Figure 5** presents the moment envelope diagram of Frame Axis 2. The bending moment distribution indicates the critical regions where flexural reinforcement is required. The moment envelope was used to determine the longitudinal reinforcement for beams. The required reinforcement areas were then compared with practical bar arrangements to ensure both structural safety and constructability.

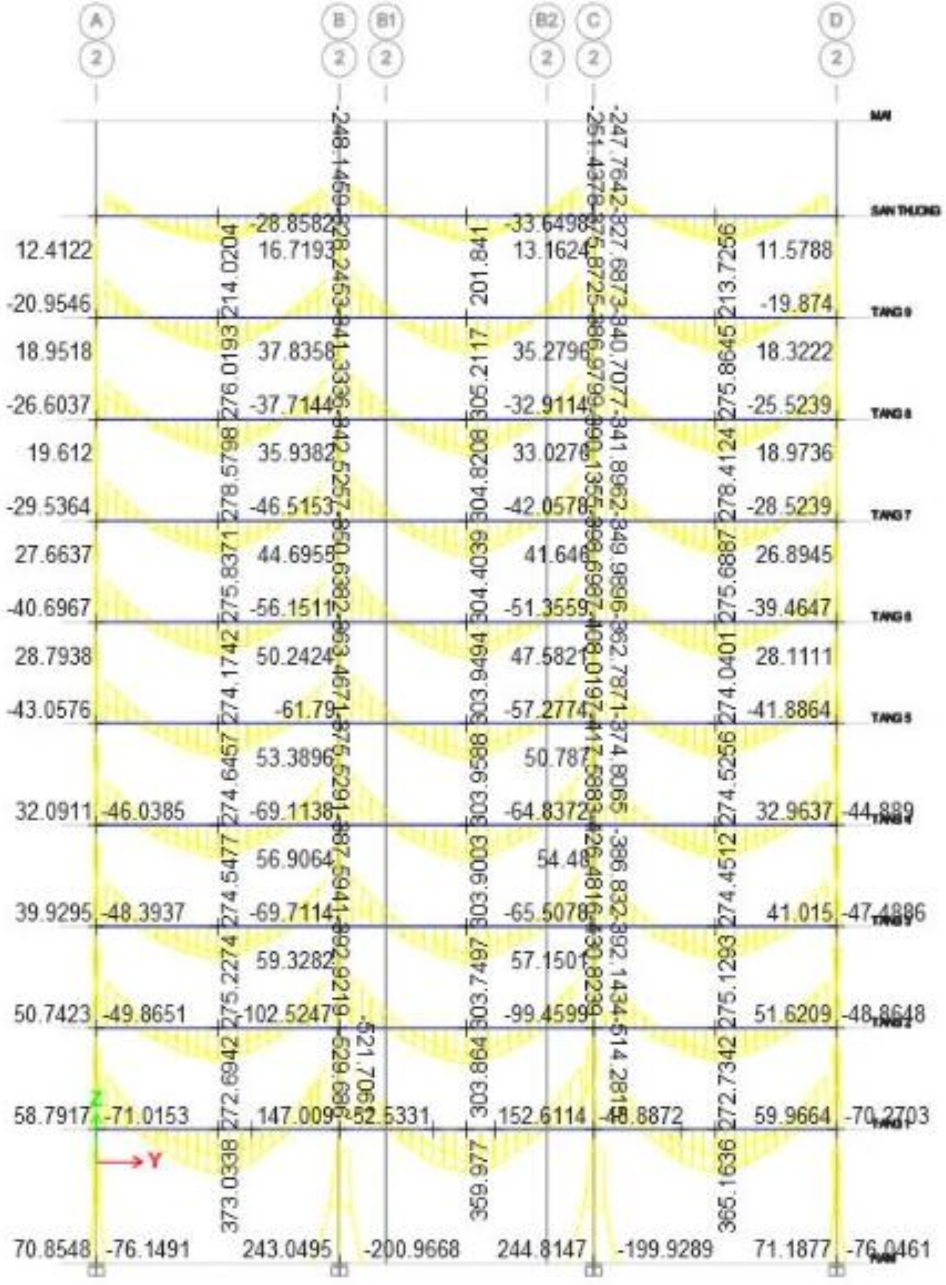


Figure 5. Moment envelope diagram of Frame Axis 2.

Figure 6 shows the shear force distribution along the frame. The maximum shear force was used to design stirrups in the beams. In the original calculation, the maximum shear force reached approximately Qmax = 349.5 kN, which required sufficient shear reinforcement to resist diagonal cracking and ensure ductile behavior. This is consistent with reinforced concrete design principles, where shear reinforcement must be provided to maintain structural integrity under combined loads (TCVN 5574:2018; Eurocode 2, 2004).

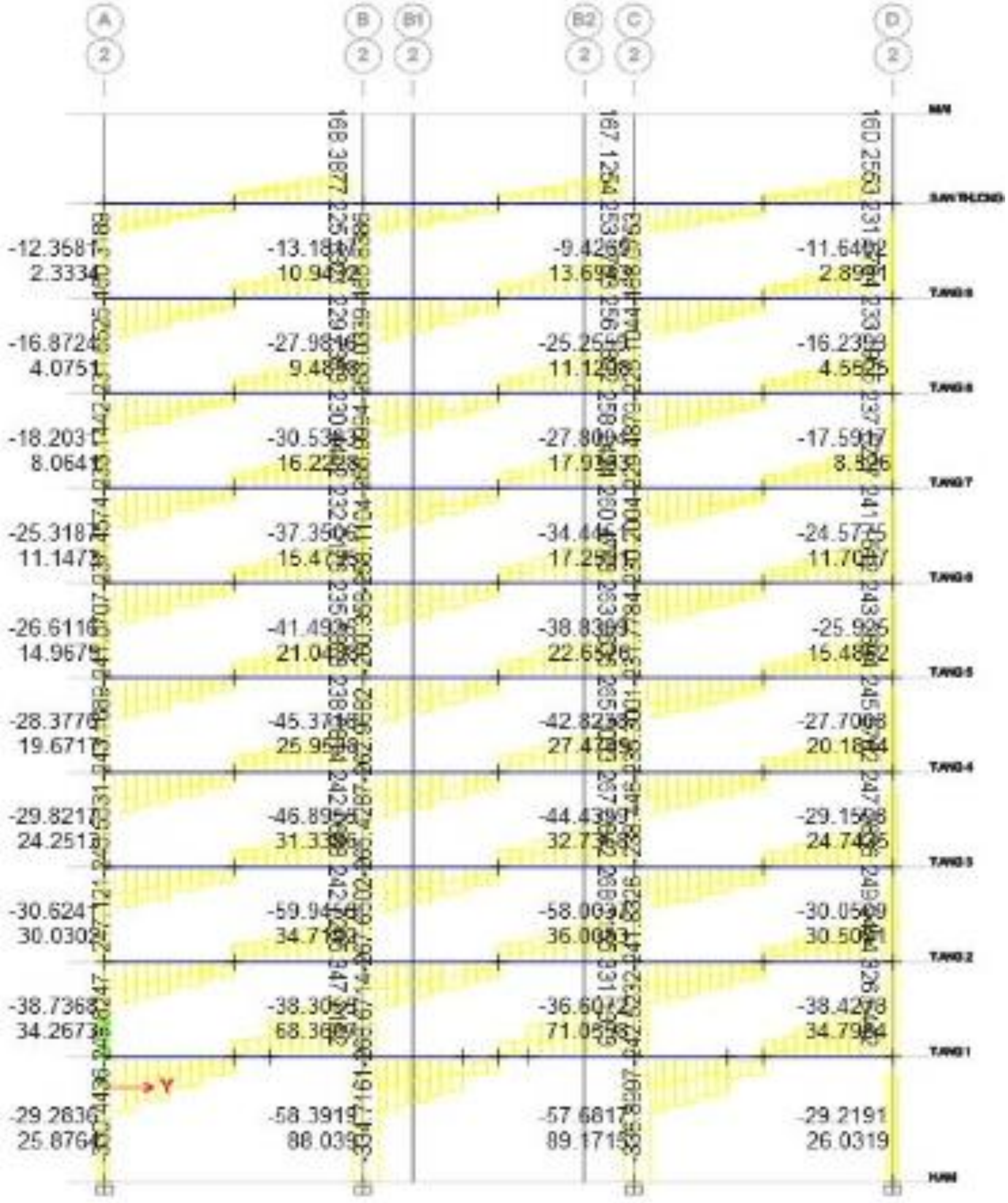


Figure 6. Shear envelope diagram of Frame Axis 2.

3.4. Beam and Column Reinforcement Design

The beam reinforcement was designed based on the maximum bending moment and shear force obtained from ETABS. Longitudinal reinforcement was selected to resist flexural demand, while stirrups were designed to resist shear force. The beam detailing used practical bar arrangements, such as 4ϕ25 longitudinal bars and stirrups spaced at approximately 100–200 mm, depending on the demand at each section. The steel area for flexural reinforcement was calculated using the bending moment demand, tensile strength of steel, effective depth, and calculation coefficient. The general design relationship can be expressed as follows: Required steel area depends on the bending moment, steel design strength, effective section depth, and design coefficient. This calculation ensured that the beam reinforcement satisfied strength requirements and could be implemented in practice. In addition to strength, ductility and constructability were considered so that reinforcement detailing could support safe structural behavior under service and extreme load conditions. Column reinforcement was designed under axial load and biaxial bending. The maximum axial load was approximately 11,400 kN. Effective length and slenderness effects were considered during the column design. The reinforcement ratio ranged from approximately 1.2% to 2.2%, satisfying the requirements of TCVN 5574:2018. This indicates that the selected reinforcement was sufficient for resisting combined axial and bending effects while remaining within acceptable design limits.

3.5. Serviceability and Displacement Performance

Serviceability was evaluated by checking the maximum horizontal displacement and inter-story drift. The horizontal displacement limit was evaluated using: $\Delta \leq h/500$, where **Δ** is the maximum horizontal displacement, and **h** is the building height. The analysis showed that the maximum horizontal displacement was within the allowable limit. This result indicates that the frame satisfied serviceability requirements under the considered load combinations. Serviceability performance is important because a building must not only resist collapse but also remain comfortable and functional during normal use. Excessive displacement can damage non-structural components, reduce user comfort, and affect the long-term performance of educational facilities. For inclusive educational facilities, serviceability is especially relevant. Students with special needs may be more affected by unsafe circulation, unstable environments, difficult evacuation routes, or structural conditions that limit comfort and accessibility. Therefore, compliance with displacement and drift limits supports not only engineering safety but also the broader goal of providing secure learning environments for all users. Inclusive built-environment studies also emphasize that educational and public spaces should consider accessibility and user needs in design (Kurniawan, 2022).

3.6. Structural Safety and Relevance to Inclusive Educational Facilities

The reinforced concrete frame met the required strength and serviceability criteria. The beams satisfied flexural and shear reinforcement requirements, while the columns satisfied axial load and biaxial bending requirements. The FEM-based ETABS model provided a reliable basis for predicting structural behavior under combined loads. This supports the use of finite element modeling as an effective tool for structural analysis and reinforced concrete design. Structural engineering contributes to inclusive education by ensuring that educational buildings remain safe, stable, and usable for all learners. A safe reinforced concrete frame provides the structural foundation for accessible classrooms, safe circulation, and reliable evacuation planning. Therefore, structural safety should be considered part of inclusive educational infrastructure. In this study, the ETABS analysis demonstrated that the frame design satisfied the required criteria under dead, live, wind, and seismic loads. This means that the structural system can support safe building use under normal and lateral loading conditions. For educational buildings, this is important because students, teachers, and school personnel depend on safe facilities for daily learning activities. For students with special needs, structural reliability becomes even more important because safe movement, predictable building behavior, and stable learning spaces can support participation and reduce risk. ETABS-based FEM analysis can support safer and more inclusive educational facility design. The technical results, including moment demand, shear demand, reinforcement design, and displacement checks, show that the frame satisfies structural requirements. Thus, structural safety supports the physical conditions needed for equitable learning participation.

The findings of this study should also be understood within the broader development of finite element-based structural analysis. FEM has been widely used not only for reinforced concrete frame analysis but also for solving complex engineering problems involving cracks, openings, stress concentration, strain energy release rate, and dynamic structural behavior. Previous studies have shown that FEM and extended FEM can be applied to analyze plates with arbitrary openings, functionally graded materials, crack propagation, stress intensity factors, and fracture behavior under different loading conditions (Nguyen, 2025a; Nguyen, 2025b; Nguyen and Huang, 2023; Nguyen, 2025c; Bai et al., 2013; Nguyen, 2025d; Ding and Li, 2013; Nguyen and Huang, 2022; Praveen and Reddy, 1998). These studies indicate that numerical methods are useful for understanding structural behavior that is difficult to evaluate through simplified manual calculation alone. The development of FEM-based analysis is also relevant for improving the safety assessment of educational buildings. Although the present study focuses on reinforced concrete frame analysis using ETABS, previous research on crack modeling, stress analysis, energy-based fracture parameters, and arbitrary openings provides a wider technical foundation for evaluating structural reliability (Erdogan and Kaya, 1985; Raju, 1987; Kim and Paulino, 2002; Bayesteh and Mohammadi, 2013; Nguyen and Huang, 2025; Singh et al., 2011). These approaches are useful because educational buildings must remain safe and serviceable under different structural conditions, especially when they are used by diverse learners, including students with special needs. For this reason, advanced numerical analysis can support safer design decisions, risk evaluation, and long-term structural monitoring. Recent engineering studies also show that FEM can be extended to nonlinear materials, dynamic systems, ultrasonic instruments, Poisson equation modeling, and stress analysis of plates with holes or defects (Nguyen and Huang, 2021; Nguyen and Huang, 2022a; Nguyen and Huang, 2022b; Nguyen, 2025e; Nguyen, 2025f; Nguyen, 2025g; Nguyen, 2025h; Dai and Xie, 2025).. These studies demonstrate the flexibility of FEM as a computational approach for solving various structural and mechanical engineering problems. In the context of inclusive educational infrastructure, this broader methodological development is important because safe learning environments require accurate structural modeling, reliable serviceability checks, and continuous improvement in engineering design practice. Therefore, the ETABS-based frame analysis in this study can be viewed as part of a wider effort to apply numerical engineering methods to support safe, accessible, and inclusive educational facilities.

4. CONCLUSION

Finite element analysis using ETABS is effective for evaluating the structural performance of a reinforced concrete frame axis in a multi-story educational building. The analysis considered dead load, live load, wind load, and seismic load based on Vietnamese design standards. The designed beams and columns satisfied strength requirements, while the horizontal displacement remained within the allowable serviceability limit. The selected reinforcement for beams and columns also met practical design and constructability requirements. Beyond technical compliance, the findings highlight the importance of structural safety in supporting inclusive educational facilities. Safe and stable buildings are essential for all users, especially students with special needs who may require accessible circulation, predictable environments, and secure evacuation conditions. Therefore, FEM-based structural design can contribute to safer, more inclusive, and more reliable educational infrastructure.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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