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Finite Element Analysis of a Multistory Reinforced Concrete Building for Safe Educational and Sports Infrastructure

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ABSTRACT

This study presents a finite element analysis of a ten-story reinforced concrete building to evaluate internal forces, structural displacements, and reinforcement requirements for safe educational and sports-related infrastructure. The structural model was developed using ETABS based on TCVN 5574:2018. Dead load, live load, wall load, finishing load, and wind load were applied through relevant load combinations. The building satisfied displacement and drift requirements, and critical bending moments, shear forces, and axial loads were identified for beam and column design. Reinforcement detailing also met code requirements. The findings highlight the importance of finite element modeling in supporting safe, reliable, and serviceable buildings for educational, physical education, and sports activity environments.

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1. INTRODUCTION

Safe educational and sports infrastructure is essential for supporting physical education, sport-related learning, training activities, and user safety in institutional environments [1]. Multistory reinforced concrete buildings are widely used in educational and institutional settings because of their strength, durability, and flexibility in accommodating classrooms, laboratories, offices, training rooms, and sport-related facilities. However, the design of reinforced concrete buildings requires accurate evaluation of internal forces, displacements, drift, and reinforcement needs. Traditional manual calculation is often insufficient for complex building systems, especially when structural responses are influenced by load combinations, wind effects, geometric configuration, and interaction between beams, slabs, and columns. Finite element method-based modeling provides a more detailed and reliable approach for analyzing structural behavior and identifying critical force demands [2-4].

Finite element analysis has been widely used to investigate structural behavior, crack propagation, stress concentration, strain energy release, stress intensity factors, and the performance of functionally graded materials and reinforced concrete systems [2-8]. Although many finite element studies focus on fracture mechanics, plate structures, and advanced material modeling, the same computational principles are also relevant for practical building design. In reinforced concrete buildings, finite element modeling enables engineers to simulate load transfer, evaluate internal forces, examine lateral displacement, and optimize reinforcement detailing. This is important for buildings used in educational and sport-related environments because structural reliability directly affects user safety and long-term serviceability.

The use of ETABS has become common in the analysis and design of multistory buildings. Through three-dimensional modeling, engineers can define material properties, beam and column sections, load patterns, load combinations, and code-based design requirements. In the context of Vietnam, reinforced concrete structures must satisfy national standards such as TCVN 5574:2018. These standards guide the design of concrete and reinforced concrete structures by regulating strength, displacement, serviceability, and reinforcement requirements. Compliance with such standards is necessary to ensure that educational and sport-related buildings remain safe under daily use and environmental loads.

For physical education and sports science, infrastructure safety should be viewed as part of the broader ecosystem of learning quality and participant protection. Unsafe or poorly designed buildings can limit the use of sports facilities, reduce user confidence, and increase risks during training or instructional activities [1]. Conversely, well-designed reinforced concrete buildings can support physical education programs by providing stable spaces for movement, practice, assessment, and institutional activities. Therefore, structural analysis contributes indirectly to sports education by ensuring that buildings and facilities used by students, instructors, and communities meet safety and serviceability requirements.

Previous research has shown the usefulness of finite element and extended finite element approaches in structural and material analysis, including crack modeling, stress intensity evaluation, and mechanical response prediction [9-16]. Other studies have applied finite element methods to nonlinear material behavior, structural health monitoring, and reinforced concrete performance [17-19]. In addition, engineering-based community service related to building safety has emphasized the importance of finite element analysis for reinforced concrete frame structures in urban building contexts [20]. These studies support the need to apply computational structural analysis to real building cases, especially where safety, serviceability, and efficient reinforcement design are required.

This study applies finite element analysis using ETABS to evaluate a ten-story reinforced concrete building in Vietnam. The analysis focuses on structural displacement, inter-story drift, internal forces in beams and columns, and reinforcement design based on TCVN 5574:2018. The novelty of this study lies in connecting reinforced concrete structural analysis with the need for safe educational and sports-related infrastructure. By positioning finite element modeling as a tool for supporting safe physical education and sport activity environments, this paper provides an engineering contribution to the broader field of physical education and sports science. The findings are expected to support safer infrastructure planning, more reliable building design, and better facility readiness for educational and sport-related use.

2. METHODS

This study used a finite element analysis approach to evaluate the structural performance of a ten-story reinforced concrete building intended to support safe educational and sports-related infrastructure. The analysis focused on structural displacement, inter-story drift, internal forces in beams and columns, and reinforcement requirements. This method was appropriate because finite element modeling allows detailed evaluation of structural behavior under combined vertical and lateral loads, which is important for buildings used for educational and sport-related activities.

2.1. Structural Model

The building analyzed in this study had a total height of 38.3 m, with a typical story height of 3.8 m. The structural system consisted of reinforced concrete frames composed of beams, slabs, and columns. A three-dimensional finite element model was developed using ETABS, as shown in **Figure 1**. The model included the grid system, material properties, floor levels, beam sections, slab elements, and column sections.

The main material and section properties used in the model were as follows:

(i) Concrete grade: B30;
(ii) Reinforcement steel: CB400-V for longitudinal reinforcement;
(iii) Reinforcement steel: CB300-T for stirrups and ties;
(iv) Typical beam section: 300 × 700 mm;
(v) Typical column section: 700 × 900 mm at lower floors, with reduced dimensions at upper floors.

These structural properties were selected to represent the main load-resisting system of the building. In the context of educational and sports-related infrastructure, the reliability of beams, columns, and slabs is important because these components support occupancy, movement, equipment, and functional spaces used for academic and physical activities.

2.2. Loading Conditions

The applied loads consisted of vertical and lateral loads commonly considered in reinforced concrete building design. These loads included structural self-weight, finishing load, wall load, live load, and wind load. The load arrangement and structural model under applied loading conditions are shown in **Figure 2**.

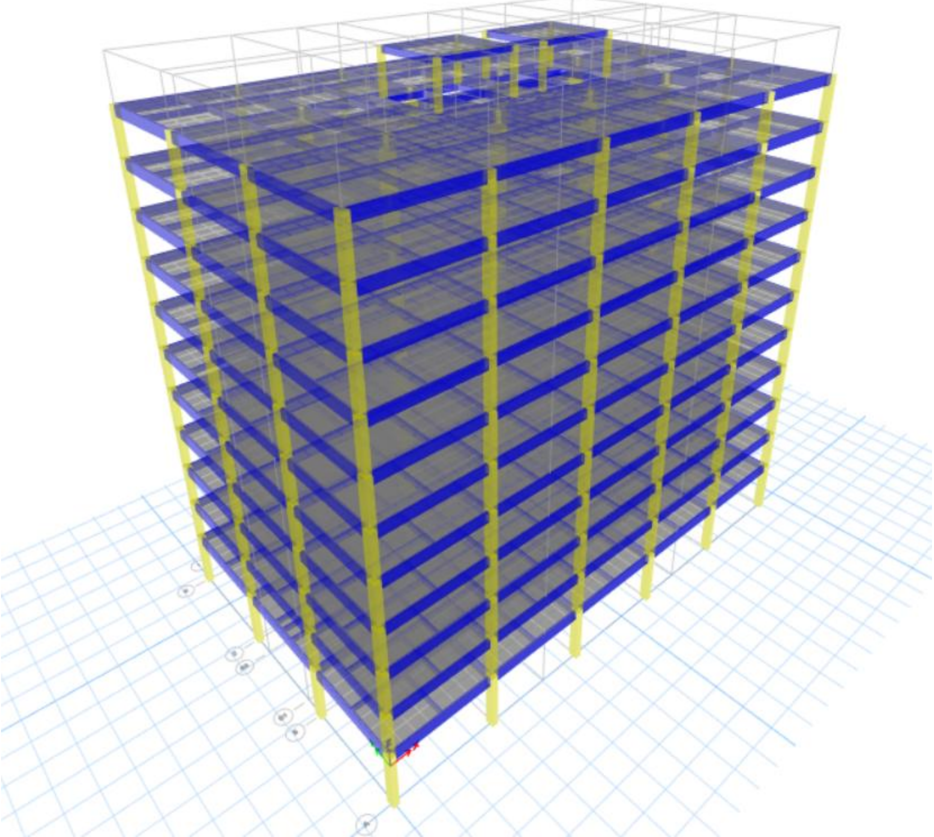

Figure 1. A three-dimensional finite element model developed in ETABS.

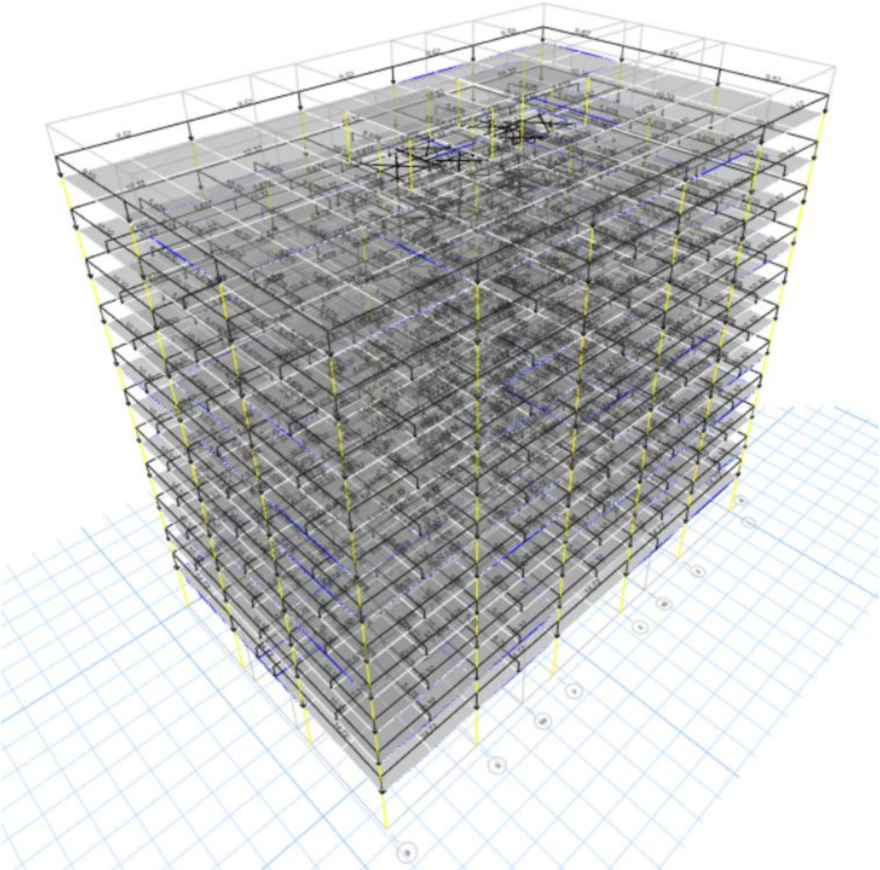

Figure 2. Applied loads in the ETABS structural model.

The loading conditions considered in the analysis were:

(i) Dead load, representing structural self-weight;
(ii) Finishing load, representing floor finishes and non-structural layers;
(iii) Wall load, representing masonry wall loads;
(iv) Live load, representing short-term imposed occupancy loads;
(v) Wind load, converted into equivalent story forces and evaluated together with reinforced concrete design requirements based on the applied Vietnamese design standards, including TCVN 5574:2018.

The inclusion of wind load was necessary because the building is a multistory structure, and lateral displacement must be controlled to ensure safety and serviceability. For spaces that may support educational, physical education, or sports-related functions, serviceability is important not only for structural safety but also for user comfort and confidence during building use.

2.3. Load Combinations

Fifteen load combinations were considered in the analysis. These combinations included basic gravity load combinations, wind load combinations, and serviceability-related conditions. An example of the load combination used in the analysis was: 1.1 Dead + 1.3 Finishing + 1.1 Wall + 2.1 WindX. Both ultimate and serviceability limit states were evaluated. The ultimate limit state was used to identify critical internal forces for strength and reinforcement design, while the serviceability limit state was used to evaluate displacement and drift requirements. The use of combined load cases is important because educational and sport-related buildings must remain safe under ordinary use as well as environmental actions such as wind.

2.4. Finite Element Analysis Procedure

The finite element analysis was performed using ETABS. The procedure consisted of several stages. First, the three-dimensional structural model was created by defining grids, floor elevations, beam and column sections, slab elements, and material properties. Second, load patterns and load combinations were assigned to the model. Third, the structural analysis was performed to obtain displacements, inter-story drift, internal forces, and stress resultants. Fourth, the maximum bending moments, shear forces, and axial loads were extracted for beams and columns.

The analysis focused on the following structural responses:

(i) Maximum roof displacement under wind load;
(ii) Inter-story drift ratio;
(iii) Bending moment envelope of beams;
(iv) Shear force envelope of beams;
(v) Axial force and biaxial bending moments in columns;
(vi) Reinforcement requirements for beams and columns.

The use of finite element modeling in this procedure is consistent with previous studies showing that FEM and XFEM approaches can support accurate structural analysis, internal force evaluation, crack behavior assessment, stress analysis, and mechanical response prediction [2-8]. Although many previous studies focused on advanced material and fracture problems, the computational basis of finite element analysis is also applicable to practical reinforced concrete building design.

2.5. Reinforcement Design

Reinforcement design was carried out using the critical force combinations obtained from ETABS. Beam reinforcement was designed based on maximum bending moments and shear forces. Column reinforcement was designed based on critical axial forces and biaxial bending moments. The design followed TCVN 5574:2018 requirements for reinforced concrete structures. For beams, longitudinal reinforcement was evaluated according to flexural demand, while shear reinforcement was determined based on the shear force envelope. For columns, longitudinal reinforcement and hoop reinforcement were designed according to axial load level, bending moment demand, and critical zone requirements. This process ensured that the structural members had sufficient strength and detailing for safe service.

2.6. Evaluation Criteria

The structural performance was evaluated based on displacement, drift, internal force, and reinforcement criteria. The roof displacement was checked against the allowable displacement limit. Inter-story drift was also evaluated to determine whether the building satisfied serviceability requirements. Internal forces in beams and columns were examined to identify critical sections for reinforcement design.

The main evaluation criteria included:

(i) Roof displacement must satisfy the allowable limit;
(ii) Inter-story drift must satisfy the code requirement;
(iii) Beam bending moments and shear forces must be used to determine reinforcement demand;
(iv) Column axial forces and biaxial moments must be used for column reinforcement design;
(v) Reinforcement detailing must satisfy the applicable code requirements.

These criteria are relevant to educational and sports-related infrastructure because buildings used for learning and physical activity must remain safe, stable, and serviceable during long-term operation. Structural safety supports not only engineering performance but also the continuity of educational and sports activities.

3. RESULTS AND DISCUSSION

3.1. Structural Displacement and Serviceability Performance

The finite element analysis showed that the ten-story reinforced concrete building satisfied the serviceability requirement for lateral displacement. Based on the ETABS displacement components, the resultant roof displacement was calculated as 0.05 m. The allowable horizontal displacement limit was determined using the height-based criterion of h/500. Since the total building height was 38.3 m, the allowable limit was 0.0766 m. Therefore, the computed roof displacement was lower than the allowable limit.

According to TCVN 5574:2018, the lateral displacement of structural members must satisfy the following condition: $f \leq f_u$ where f is the actual displacement and f_u is the allowable displacement limit. For the analyzed building, the total height was h = 38.3 m. Therefore, the allowable horizontal displacement was calculated as: $\frac{\mathrm{h}}{500} = \frac{38{,}3}{500} = 0{,}0766\ (\mathrm{m})$.

Based on the ETABS results, the roof displacement was f = 0.05 m. Thus, f is less than 0.0766 m. This shows that the building satisfies the roof displacement requirement. The inter-story drift was also checked using the following criterion: $\Delta/h \leq 1/500$. The maximum drift ratio obtained from the analysis was 0.0007, which is less than 1/500. Therefore, the building also satisfies the inter-story drift requirement.

Table 1 shows the summary of displacement and drift performance. The maximum inter-story drift ratio was 0.0007, which was smaller than the allowable drift limit of 1/500. This indicates that the structural system has sufficient lateral stiffness under wind loading. For educational and sports-related infrastructure, this result is important because excessive lateral displacement may affect user comfort, safety perception, and long-term serviceability of spaces used for learning, physical activity, and institutional functions.

Table 1. Summary of displacement and drift performance.

STRUCTURAL RESPONSE	COMPUTED VALUE	ALLOWABLE LIMIT	INTERPRETATION
Roof displacement	0.05 m	0.0766 m	Satisfies the displacement requirement
Inter-story drift ratio	0.0007	1/500	Satisfies the drift requirement

The displacement results also show the importance of finite element modeling in evaluating multistory reinforced concrete buildings. Through ETABS analysis, the designer can identify whether the building remains within acceptable serviceability limits before reinforcement detailing is finalized. This supports safer infrastructure planning for buildings that may accommodate classrooms, offices, training areas, physical education spaces, or multipurpose sport-related activities.

3.2. Internal Forces in Beams

The internal force analysis identified critical bending moment and shear force demands in beams along axis 2. The maximum bending moment at the first-floor support reached 537.38 kNm, while the maximum mid-span moment was 373.07 kNm. These values indicate that the lower-floor beams experienced higher force demands due to accumulated gravity loads and frame action. The moment envelope is presented in **Figure 3**.

The shear force envelope also showed critical shear demand along axis 2. The maximum shear force reached 349.5 kN, as shown in **Figure 4.** This value was used as the basis for shear reinforcement design in the beam members. As shown in **Table 2**, the finite element model made it possible to identify the most critical regions for beam reinforcement. The support moment controlled the design of negative reinforcement, while the mid-span moment controlled positive reinforcement. The shear force envelope provided the basis for determining stirrup spacing. These results show that FEM-based analysis is useful for obtaining accurate internal force distributions, especially in multistory reinforced concrete frames subjected to combined gravity and wind effects [2-8].

In the context of safe educational and sports infrastructure, beam performance is particularly important because beams support floor systems, occupancy loads, equipment loads, and activity spaces. Buildings used for physical education or sport-related functions may experience varying occupancy patterns and functional demands. Therefore, reliable identification of beam forces contributes to safe and serviceable facility use.

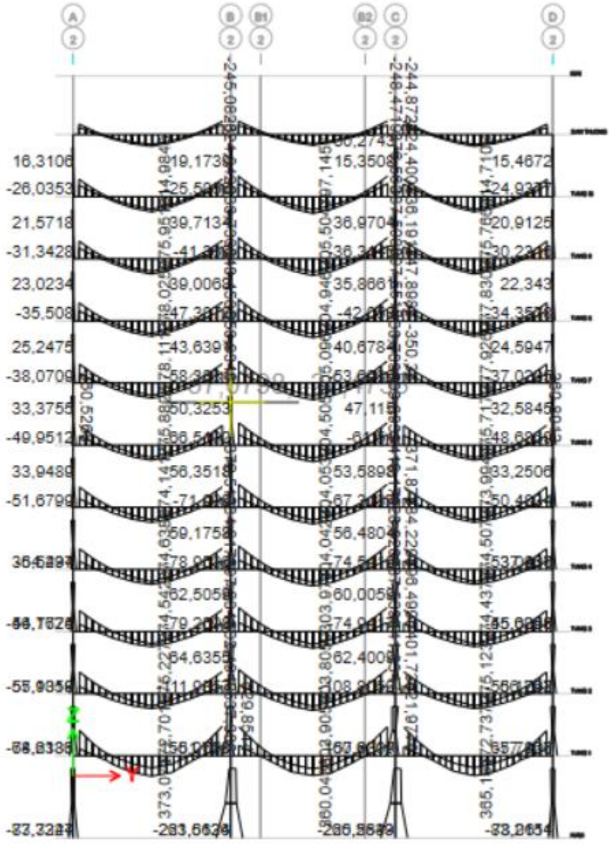

Figure 3. Moment envelope diagram of axis 2.

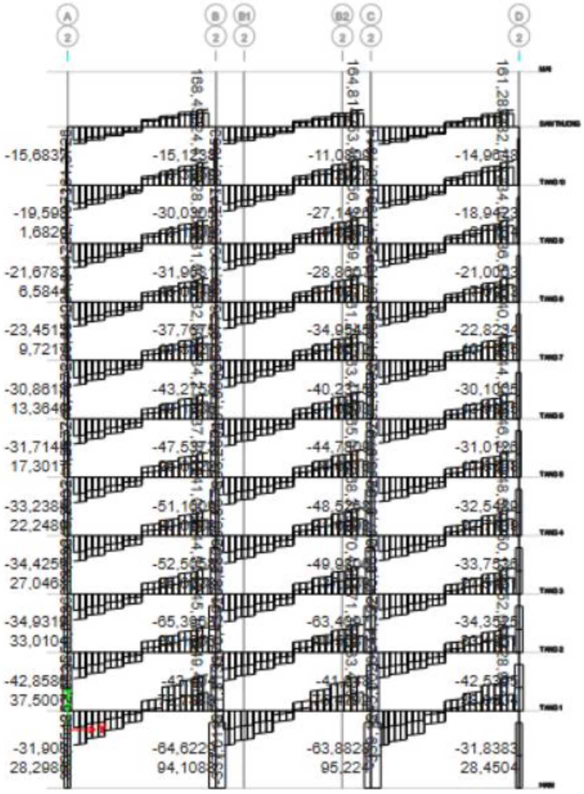

Figure 4. Shear force envelope diagram of axis 2.

Table 2. Summary of critical internal forces in beams.

BEAM RESPONSE	CRITICAL VALUE	LOCATION / CONDITION	DESIGN IMPLICATION
Maximum support bending moment	537.38 kNm	First-floor support, axis 2	Governs negative reinforcement at support zones
Maximum mid-span bending moment	373.07 kNm	Beam span, axis 2	Governs positive reinforcement at mid-span
Maximum shear force	349.5 kN	Beam critical region, axis 2	Governs stirrup design and shear reinforcement spacing

3.3. Internal Forces in Columns

The analysis also identified critical axial forces and biaxial bending moments in columns. Column C29 experienced an axial load of -6092 kN, with corresponding bending moments of Mx = -0.02 kNm and My = -258.47 kNm at the first floor. This result indicates that lower-floor columns are critical because they carry accumulated vertical loads from upper floors and resist bending effects caused by lateral actions. Column design is essential in multistory reinforced concrete buildings because columns serve as the main vertical load-resisting members. Failure or insufficient detailing of columns may affect the stability of the entire structural system. Therefore, the axial force and biaxial moment results from ETABS provide an important basis for reinforcement design and safety evaluation. The column results also confirm the importance of three-dimensional modeling. In a multistory frame, columns are not subjected to axial load alone. They may also experience bending moments from frame action, load eccentricity, and lateral effects. FEM-based analysis can capture these combined force effects more effectively than simplified manual procedures, especially for buildings with multiple floors and complex load combinations.

3.4. Reinforcement Design Results

The reinforcement design was conducted based on the critical internal forces obtained from the finite element analysis. For beams, the longitudinal reinforcement ratios ranged from 0.8% to 1.5%, which were within code limits. Shear reinforcement was provided as Ø8a100 at end zones and Ø8a200 at mid-span regions. This arrangement reflects the higher shear demand near supports and the lower shear demand toward the middle of the span. For columns, the longitudinal reinforcement area ranged from 4613 to 16295 mm², depending on the axial force level and bending moment demand. Hoop reinforcement was designed using Ø8 ties at 100 mm spacing in critical zones. These reinforcement details were selected to satisfy strength and ductility requirements according to TCVN 5574:2018.

As shown in **Table 3**, the reinforcement design satisfied code-based requirements for beams and columns. The variation in reinforcement demand reflects the different internal force levels in structural members. Lower-floor members generally required greater reinforcement because they resisted higher accumulated gravity and lateral effects. This finding supports the use of finite element modeling as a practical design tool for safe, efficient, and economical reinforcement planning.

Table 3. Summary of reinforcement design results.

STRUCTURAL MEMBER	REINFORCEMENT RESULT	INTERPRETATION
Beams	Longitudinal reinforcement ratio ranged from 0.8% to 1.5%	Within code limits and suitable for flexural demand
Beam shear reinforcement	Ø8a100 at end zones and Ø8a200 at mid-span	Provides stronger shear resistance near supports
Columns	Longitudinal reinforcement area ranged from 4613 mm² to 16295 mm²	Adjusted according to axial force and bending moment demand
Column hoop reinforcement	Ø8 ties at 100 mm spacing in critical zones	Supports confinement and detailing requirements

3.5. Integrated Discussion

The results show that the finite element model successfully identified displacement behavior, beam internal forces, column force demands, and reinforcement requirements for the ten-story reinforced concrete building. The structure satisfied serviceability criteria for roof displacement and inter-story drift. In addition, the critical force results provided a clear basis for designing beam and column reinforcement. These findings confirm that FEM-based analysis is effective for evaluating structural safety and optimizing reinforcement in multistory reinforced concrete buildings [9-16].

Compared with simplified manual calculations, finite element analysis provides more detailed information on force distribution, displacement response, and member-level demands. This is especially useful for multistory buildings where gravity load, wind load, frame interaction, and stiffness distribution influence the structural response. FEM also helps engineers locate critical sections and design reinforcement more accurately, reducing the risk of unsafe or uneconomical design decisions.

The relevance of this study lies in its contribution to safe educational and sports-related infrastructure. Physical education and sports activities require safe buildings and reliable facilities. Classrooms, training halls, indoor activity areas, and multipurpose institutional buildings must remain stable and serviceable under vertical and lateral loads. Structural safety is therefore connected to the quality of physical education and sports environments because it supports safe movement, user confidence, facility continuity, and institutional readiness.

The findings also show that structural engineering analysis can support the broader development of sports education facilities. A building used for physical education or sport-related purposes must not only provide space but also satisfy safety, stiffness, and serviceability requirements. The use of ETABS and FEM-based analysis helps ensure that such facilities can accommodate educational and physical activities without excessive displacement, inadequate reinforcement, or critical structural weakness. However, this study has limitations. The analysis assumed linear elastic behavior and idealized boundary conditions. In actual buildings, structural responses may be influenced by material nonlinearity, construction imperfections, creep, shrinkage, cracking, and long-term service effects. Future studies should incorporate nonlinear analysis, time-dependent effects, and structural health monitoring to obtain a more comprehensive understanding of building performance [17-20]. Further research may also examine sports halls, gymnasiums, and physical education facilities with wider spans, dynamic activity loads, and crowd-induced vibration effects.

4. CONCLUSION

This study applied finite element analysis using ETABS to evaluate the structural performance of a ten-story reinforced concrete building for safe educational and sports-related infrastructure. The results showed that the building satisfied roof displacement and inter-story drift requirements under wind loading. Critical bending moments, shear forces, and axial loads were identified for beams and columns, providing a reliable basis for reinforcement design. The reinforcement results showed that beam and column detailing met code-based requirements according to TCVN 5574:2018. These findings confirm that FEM-based analysis is useful for designing safe, serviceable, and efficient multistory buildings. For physical education and sports science, safe infrastructure is important because it supports secure learning spaces, physical activity, sport-related programs, and long-term facility use. Future studies should include nonlinear behavior, time-dependent effects, structural health monitoring, and dynamic loading conditions in sports facilities.

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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