



Research Article

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Influence of Element Types and Mesh Sizes on the Precision of Deflection Analysis in Finite Element Method for Civil Infrastructure Applications

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Abstract

This study investigates the influence of different finite element types and mesh sizes on the accuracy of deflection calculations in civil engineering structural analysis. The research examines three distinct element configurations: linear quadrilateral, quadratic quadrilateral and linear triangular elements with varying mesh densities. Through systematic numerical analysis, deflection values were compared against theoretical benchmarks to evaluate convergence behavior and computational efficiency. Element formulation profoundly influences simulation efficiency. Quadratic quadrilaterals perform very well, offering high accuracy (99.8%) even when using few mesh elements, showing they work best in this situation. Conversely, linear quadrilaterals require moderate refinement for accuracy and linear triangles demand significant computational resources due to their sluggish convergence and inherent inefficiency. The findings indicate that mesh refinement consistently improves accuracy across all element types, but the rate of convergence varies substantially. Quadratic elements provide optimal balance between computational cost and precision, making them preferable for complex structural analyses. This paper contributes to the optimization of the Finite Element Method (FEM) giving a framework for improving precision and efficiency in civil infrastructure design and computing.

Keywords: Finite Element Method; Mesh Convergence; Element Types; Deflection Analysis; Civil Infrastructure; Numerical Analysis; Structural Engineering; Computational Mechanics

Introduction

The Finite Element Method (FEM) has become an indispensable tool in modern civil engineering for analyzing complex structural behaviors and predicting performance under various loading conditions [1]. The fidelity and robustness of Finite Element Analysis (FEA) simulations are predominantly governed by the discretization scheme, specifically the choice of element formulation and the degree of mesh refinement [2]. Consequently, comprehending the interplay between these variables and numerical precision is paramount for practitioners to make judicious choices pertaining to computational economy and predictive fidelity. The choice of element type significantly influences the quality of finite element solutions in structural analysis applications [3]. Linear elements, defined by first-order interpolation functions, offer computational

economy and straightforward implementation. However, this simplicity comes at the expense of fidelity, often necessitating profound mesh refinement to converge upon solutions of acceptable accuracy [4]. In stark contrast, quadratic elements employ second-order interpolation, which confers a superior capacity to capture complex stress fields and model curved geometries with significantly sparser discretization [5]. This improved ability to converge helps reduce the need for very detailed adjustments. In the end, finding the right balance between the cost of calculations and how accurate the results are is a key part of design, and it needs to be carefully considered depending on the specific needs of each engineering project. Mesh convergence studies show that making the mesh finer usually leads to more accurate solutions, which follows well-known mathematical rules from numerical approximation theory

[6]. However, the rate of convergence varies significantly depending on element formulation, problem geometry, and loading conditions [7]. For civil infrastructure applications, where accurate deflection prediction is paramount for serviceability limit state verification, understanding these convergence characteristics is essential [8].

Previous research has extensively investigated mesh sensitivity in various structural configurations. Liu and Quek [9] demonstrated that element aspect ratio and orientation significantly affect solution accuracy in plate bending problems. In 1987, Zienkiewicz and Zhu developed adaptive mesh refinement, utilizing error estimates to significantly enhance computational efficiency. Later, as processing power advanced, researchers like Fish and Belytschko [10] were able to perform sweeping parametric studies to rigorously assess element behavior in various applications. The quadrilateral element family has received considerable attention due to its versatility in modeling regular geometries typical in civil engineering structures [11]. Linear quadrilateral elements, while computationally efficient, may exhibit shear locking phenomena in thin structural members, potentially compromising solution accuracy [12]. The choice of finite element type involves a critical engineering trade-off. Triangular shapes work well for fitting into complicated shapes and are great for flexible meshing, as shown by Peraire et al. [13]. However, their simple form only gives a flat stress estimate, which means you need a lot of small triangles to get accurate results, and this makes the calculations more expensive, according to Hinton and Owen in 1979. Conversely, quadratic quadrilateral elements significantly improve interpolation and accuracy, though each element is more computationally expensive [14]. The design challenge lies in balancing the computational overhead of increased element numbers against the gains achieved

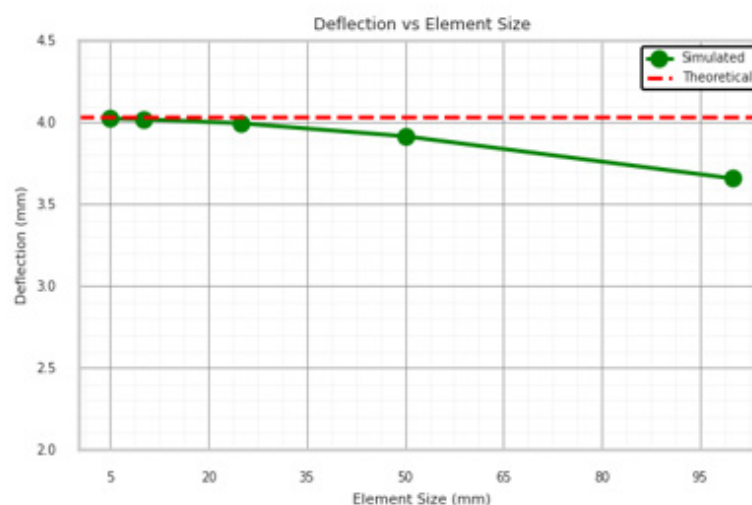
from superior geometric conformity and stress resolution.

Mesh density effects on solution convergence have been systematically studied across various element formulations. Theoretical models predict that displacement errors diminish with the square of the mesh size for linear elements and the cube for quadratic elements during h-refinement [15]. Nevertheless, the presence of geometric intricacies and complications in implementing boundary conditions frequently causes empirical results to diverge from these theoretical ideals. Adaptive mesh refinement techniques bridge this gap by optimizing computational efficiency to maintain required accuracy levels [16]. The advent of posteriori error estimators has been pivotal, enabling automatic mesh adaptation based on local error data and drastically reducing the manual effort traditionally required in mesh generation [17]. These capabilities are particularly transformative for civil infrastructure analysis, where computational speed is a key determinant of feasible design exploration. This automation is crucial, as it enhances computational efficiency, which in turn directly expands the scope for iterative design optimization in civil infrastructure projects.

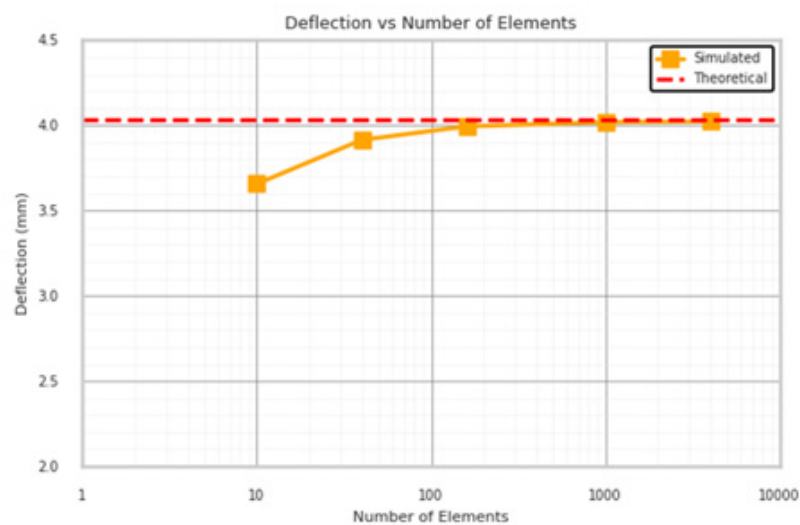
The primary objective of this investigation is to quantify the impact of finite element selection and mesh density on the precision of computed deflections through a rigorously controlled numerical experimental framework. By comparing simulation results against known theoretical solutions, convergence characteristics can be established for different element formulations. This research offers actionable strategies for civil engineering FEA, focusing on a balanced approach that satisfies critical accuracy standards while remaining within feasible computational bounds [18-22].

Methodology

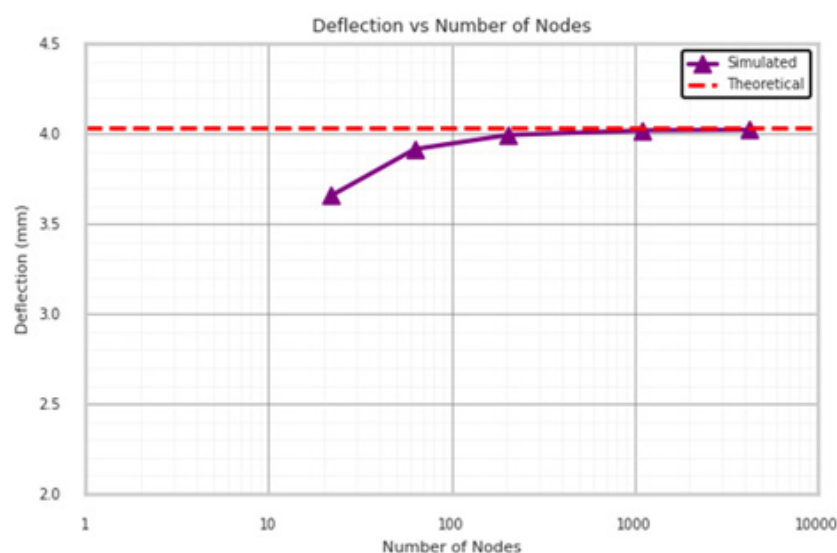
Case-1: Mesh size dependency on Linear quadrilateral simulation



Graph 1: Relation of Deflection with Element Size.



Graph 2: Relation of Deflection with No. of Elements.



Graph 3: Relation of Deflection with No. of Nodes.

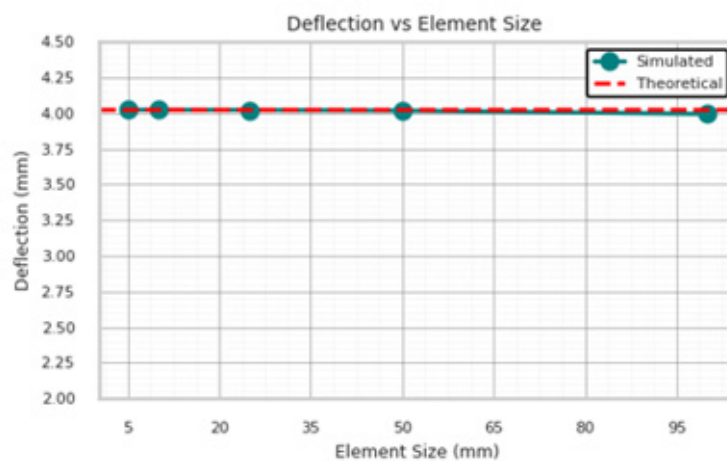
Table 1: Mesh size dependency on Linear quadrilateral simulation.

	Element Size (mm)	No. of Elements	No. of Nodes	Deflection (mm)	Ratio
Theoretical	-	-	-	4.031	1
Simulated (Linear quadrilateral)	100	10	22	3.657	0.907
	50	40	63	3.915	0.971
	25	160	205	3.994	0.991
	10	1000	1111	4.019	0.997
	5	4000	4221	4.023	0.998

From the above graphs

- The element size is varied while using linear quadrilateral elements.
- From Graphs 1 to 3, as the element size decreases from 100 mm to 5 mm, both the number of elements and nodes increase significantly.
- This indicates a finer mesh, improving the accuracy of the simulation.
- As the mesh becomes finer, the simulated deflection values approach the theoretical deflection of 4.031 mm.
- The deflection values show a gradual convergence toward the theoretical result.
- The ratio (simulated/theoretical deflection) also approaches 1.000, indicating higher precision with smaller element sizes

Case-2: Element type dependency on Quadratic quadrilateral simulation



Graph 4: Relation of Deflection with Element Size.

Table 2: Element type dependency on Quadratic quadrilateral simulation.

	Element Size (mm)	No. of Elements	No. of Nodes	Deflection (mm)	Ratio
Theoretical	-	-	-	4.031	1
Simulated (Quadratic quadrilateral)	100	10	53	3.995	0.991
	50	40	165	4.019	0.997
	25	160	569	4.023	0.998
	10	1000	3221	4.024	0.998
	5	4000	12441	4.024	0.998

Table 3:

	Element Size (mm)	No. of Elements	No. of Nodes	Deflection (mm)	Ratio
Theoretical	-	-	-	4.031	1
Simulated (Linear triangle)	100	40	32	2.158	0.535
	50	82	64	2.666	0.661
	25	328	209	3.595	0.892
	10	2392	1307	3.967	0.984
	5	9198	4820	4.009	0.995

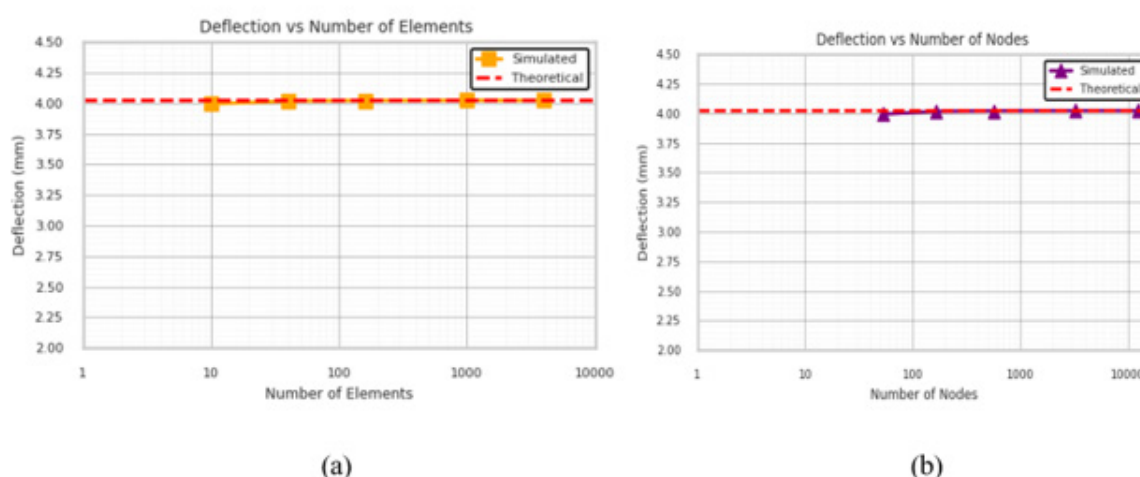
In the second case, the element type varies from linear quadrilateral to quadratic quadrilateral, while the element size remains variable

- Graphs 4 to 5 (a, b), switching to quadratic elements results in a significant increase in the number of nodes, which generally leads to improved accuracy.
- Compared to Table 1 and Graphs 1 to 3, the quadratic quadrilateral elements produce more accurate results, even at

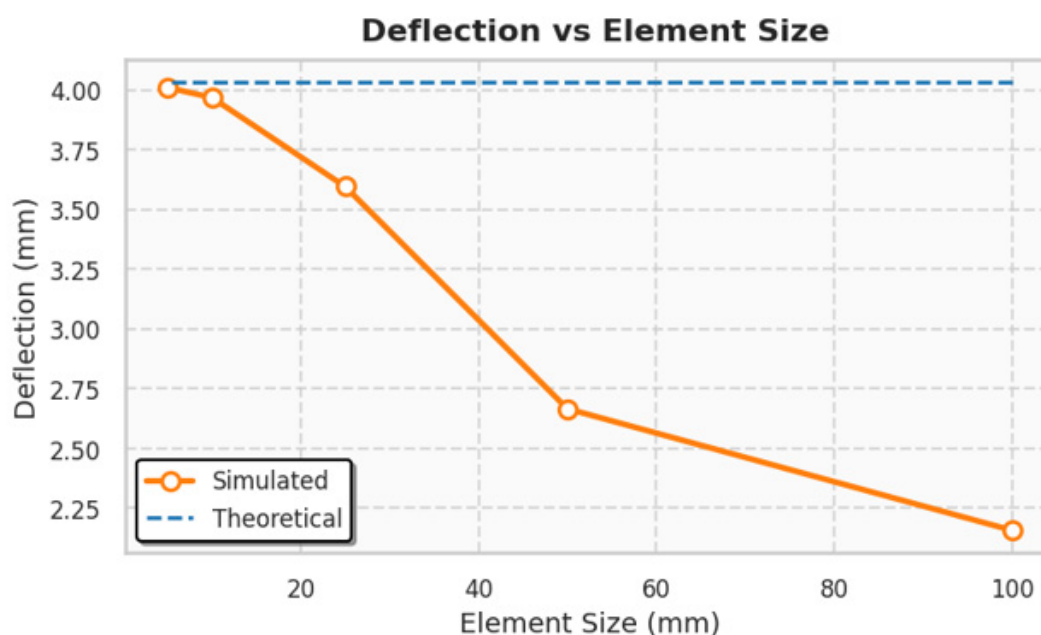
larger element sizes.

- This improvement is due to the quadratic interpolation functions, which better capture higher-order variations in the solution.
- The simulated deflection values are consistently closer to the theoretical value of 4.031 mm.
- The corresponding ratios also approach 1.000, indicating higher precision with quadratic elements.

Case-3: Element shape dependency on Linear triangle simulation



Graph 5 (a): Relation of Deflection with No. of Elements; (b): Relation of Deflection with No. of Node.



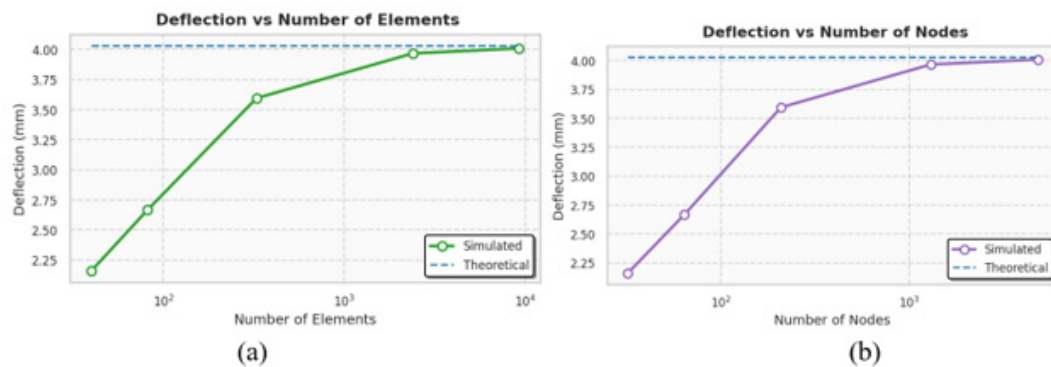
Graph 6: Relation of Deflection with Element Size.

In the third case, the element shape is changed to a linear triangle, while the element size remains variable.

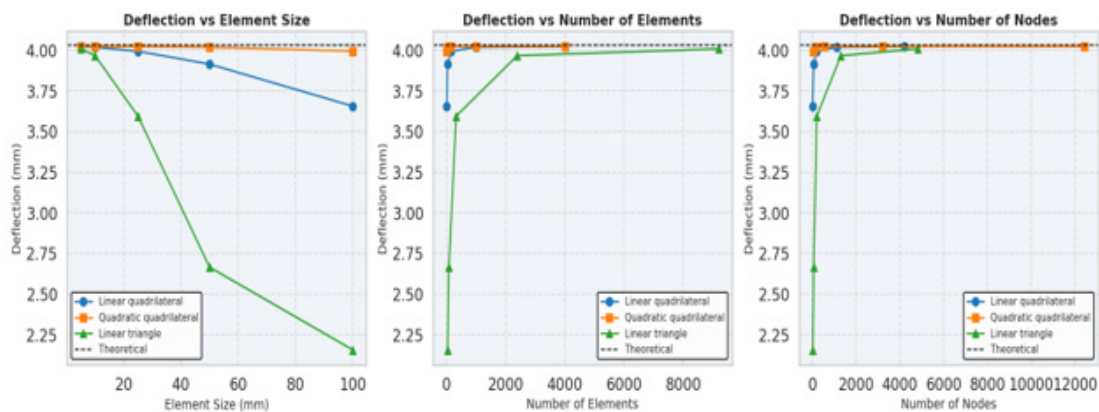
- Graphs 6 to 7 (a, b), as the element size decreases from 100 mm to 5 mm, the number of elements and nodes increases significantly, resulting in a finer mesh.
- This mesh refinement leads to simulated deflection values that gradually approach the theoretical value of 4.031 mm.

- However, the accuracy of linear triangle elements is lower compared to linear quadrilateral elements.
- The simulated deflection values are smaller, and the ratios are noticeably lower than the theoretical value.
- This indicates that linear triangles provide less precision, even with mesh refinement.

Graphical Representations of the Influence of Element Type and Size on the Precision of Simulated Value OF deflection



Graph 7 (a): Relation of Deflection with No. of Elements; (b): Relation of Deflection with No. of Nodes.



Observations from the Graphs

a. Accuracy Improvement with Mesh Refinement:

- For all element types, deflection values approach the theoretical value (4.031 mm) as element size decreases (mesh gets finer).
- This trend is clearest for Quadratic Quadrilateral and Linear Quadrilateral elements.

b. Element Type Performance:

- Quadratic Quadrilateral elements show excellent convergence early, reaching 99.8% of theoretical deflection even with moderately refined meshes.
- Linear Quadrilateral elements also perform well, with accuracy increasing steadily and reaching ~99.8% accuracy at the finest mesh.

- Linear Triangle elements show slower convergence, especially with coarser meshes, and need significantly more elements and nodes to achieve similar accuracy.

C. Efficiency vs. Accuracy:

- Quadratic Quadrilateral elements offer the best balance between accuracy and computational effort (fewer elements and nodes needed for high accuracy).
- Linear Triangle elements, despite requiring far more elements and nodes, lag behind in accuracy until the mesh is very fine.

d. Graph Trends:

- The curves for Quadratic and Linear Quadrilateral elements stabilize quickly and closely follow the theoretical deflection.
- The triangle element curve shows a larger error at coarse mesh sizes and improves gradually.

It is important to recognize that these conclusions are drawn from the specific simulation data provided. The impact of element size and quantity on accuracy can differ depending on the nature of the problem and the structural behavior involved. The selection of element type should be based on the particular requirements of the analysis. Quadratic quadrilateral elements are generally preferred due to their higher accuracy and faster convergence, especially in complex scenarios. In contrast, linear quadrilateral and triangular elements are simpler and computationally less demanding but may sacrifice accuracy and require finer meshes to achieve similar results.

Conclusion

This study conclusively demonstrates that the selection of element type and mesh size is fundamental to achieving accurate and efficient deflection calculations in Finite Element Analysis (FEA) for civil engineering. The study shows that quadratic quadrilaterals work best, achieving 99.8% accuracy even with a coarse mesh. Linear quadrilaterals need a much finer mesh to get the same level of accuracy, which makes the process slower and more expensive. Triangular elements are the least efficient, requiring many more elements to reach similar results because they don't improve as quickly. The research also shows that while making the mesh finer generally improves the results, how fast the solution improves and how much computing power is needed depends a lot on the type of elements used. For practicing engineers, the key takeaway is the necessity of prioritizing both computational resources and accuracy. This often makes quadratic quadrilateral elements the most advantageous choice for complex projects, where they provide an optimal equilibrium between model performance and practical feasibility.

Recommendations

Based on the comprehensive analysis conducted in this study, the following recommendations are proposed for finite element analysis in civil engineering applications:

Element Selection Guidelines

- Prioritize quadratic quadrilateral elements for general structural analysis due to their optimal balance between accuracy and computational efficiency
- Utilize linear quadrilateral elements for preliminary analyses or when computational resources are severely limited
- Reserve linear triangular elements for complex geometries where quadrilateral meshing is impractical, while acknowledging the need for finer meshes

Mesh Design Strategies

- Implement systematic mesh convergence studies before finalizing element sizes for critical structural components
- Target element sizes of 10-25 mm for moderate accuracy requirements when using quadratic elements
- Reduce element sizes to 5-10 mm when high precision is essential for serviceability limit state verification

Computational Optimization

- Establish accuracy thresholds (e.g., 99% of theoretical values) as convergence criteria for iterative mesh refinement
- Consider adaptive mesh refinement techniques for problems with high stress gradients or geometric complexity
- Balance mesh density with available computational resources and project timeline constraints

Quality Assurance Practices

- Validate finite element models against analytical solutions or experimental data whenever possible
- Document mesh sensitivity studies as part of standard engineering analysis procedures
- Implement peer review processes for critical infrastructure finite element analyses

Future Research Directions

- Investigate higher-order elements (cubic and beyond) for specialized applications requiring exceptional accuracy
- Develop automated mesh optimization algorithms specific to civil infrastructure geometries
- Explore parallel computing implementations to mitigate computational costs associated with fine mesh densities

Industry Implementation

- Establish organizational guidelines for element type selection based on project requirements and complexity
- Provide training programs for engineers on finite element best practices and mesh convergence principles
- Develop standardized verification procedures for finite element analyses in civil engineering projects

These recommendations aim to enhance the reliability and efficiency of finite element analyses in civil engineering practice while maintaining the highest standards of structural safety and performance prediction.

Acknowledgement

None.

Conflict of Interest

No conflict of interest.

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