International Journal of Multidisciplinary Academic Studies and Research (IJMASR)
Registered with MSME, Govt. of India: UDYAM-MH-20-0329275
Available at https://ijmasr.org Volume-1, Issue-3, March 2026, Page- 390-400.

To Cite This Article
Roshan M. Patle, & Prof. Girish H. Sawai. (2026). Finite Element Analysis and Design of Bridge Pier Pile Foundation Subjected to Dynamic Moving Load And Induced Vibration. International Journal of Multidisciplinary Academic Studies and Research (IJMASR), 1(3), 390–400. https://doi.org/10.5281/zenodo.19789169

Article Info
Received: 28th March 2026, Accepted: 29th March 2026, Published: 30th March 2026.

Finite Element Analysis and Design of Bridge Pier Pile Foundation Subjected to Dynamic Moving Load And Induced Vibration

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Abstract: - The rapid growth of transportation infrastructure and increasing demand for safe and durable bridge structures have made it essential to study the behaviour of bridge foundations under dynamic loading conditions. The present research work focuses on the finite element analysis and design of bridge pier pile foundation subjected to dynamic moving load and induced vibration. The study aims to evaluate the structural performance of bridge systems considering seismic loading, moving loads, and soil–structure interaction (SSI) using advanced numerical techniques. A three-dimensional finite element model of the bridge structure along with pile foundation and surrounding soil is developed using ANSYS software. The analysis is carried out by applying time-history seismic loading corresponding to different earthquake zones (Zone III, IV, and V). In addition to seismic loads, the effect of dynamic moving loads is also considered to simulate real traffic conditions. The behaviour of the structure is analysed in terms of displacement, stress distribution, bending moment, shear force, vibration characteristics, and factor of safety. A comparative study is performed using three different materials, namely structural steel, carbon fibre reinforced steel, and epoxy fibre reinforced steel, to determine the most suitable material for pile foundation under dynamic conditions. The results indicate that the bridge structure exhibits nonlinear behaviour under seismic loading, with deformation increasing as the intensity of the earthquake increases. Maximum displacement and stress are observed in structural steel, while carbon fibre reinforced steel shows minimum deformation, better stress distribution, and higher energy absorption capacity. The pile foundation analysis reveals that soil–structure interaction plays a significant role in reducing vibration and improving stability. The maximum stress concentration occurs at the pile–soil interface, and the displacement increases with increasing seismic intensity. The factor of safety is found to be 2.1 for structural steel, 3.1 for epoxy fibre reinforced steel, and 3.8 for carbon fibre reinforced steel, indicating that carbon fibre reinforced material provides the highest safety and reliability.

Keywords: - Finite Element Analysis, Bridge Pier, Pile Foundation, Dynamic Loading, Moving Load, Seismic Analysis, Soil–Structure Interaction, Vibration Analysis

I. INTRODUCTION

Bridge engineering is one of the most important branches of civil engineering, playing a vital role in the development of transportation networks and economic growth. Bridges provide connectivity across rivers, valleys, railways, and highways, enabling safe and efficient movement of people and goods. With rapid urbanization and increasing traffic demands, modern bridges are required to carry heavier loads, sustain higher speeds, and perform efficiently under complex environmental conditions. A bridge structure mainly consists of two parts: superstructure (deck, girders, slab) and substructure (piers, abutments, and foundations). Among these, the foundation system, particularly pile foundation, is the most critical component because it transfers the entire load of the structure safely to the ground. In recent years, bridges are increasingly subjected to dynamic loading conditions such as moving vehicles, high-speed trains, seismic forces, wind loads, wave action, and impact loads. These dynamic loads produce vibrations in the structure, which significantly affect the performance of the bridge and its foundation system.

II. METHODOLOGY

GEOMETRY MODELLING OF BRIDGE STRUCTURE:

The bridge structure is modelled as a three-dimensional frame system consisting of beams, columns, and pile foundation. The modelling is carried out considering realistic dimensions suitable for medium-span bridge structures.

Geometric Details:

1. Column size = 0.35 m × 0.45 m
2. Beam size = 0.23 m × 0.45 m
3. Height of pier = 5 m
4. Foundation depth = 2 m
5. Pile diameter = 350 mm
6. Pile length = 1 m (model scale)

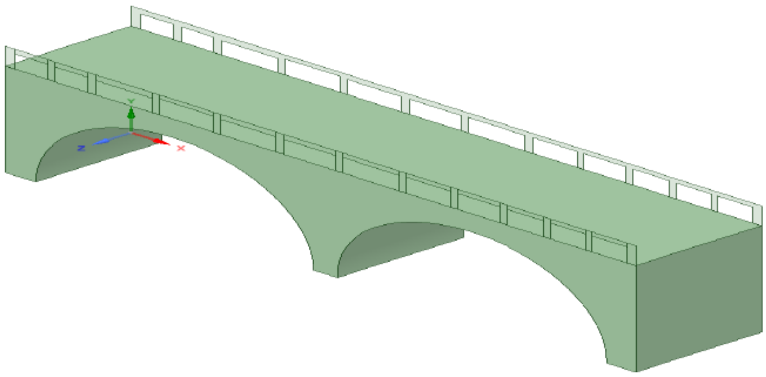

Figure 3.1: Isometric view of bridge structure

MODELLING OF PILE FOUNDATION AND SOIL:

The pile foundation is modelled as a cylindrical element embedded in soil. The soil is represented as a 3D block to simulate realistic interaction.

Soil Model:

1. Soil block size = 1 m × 1 m × 1 m
2. Soil type = Homogeneous (simplified)
3. Behaviour = Elastic

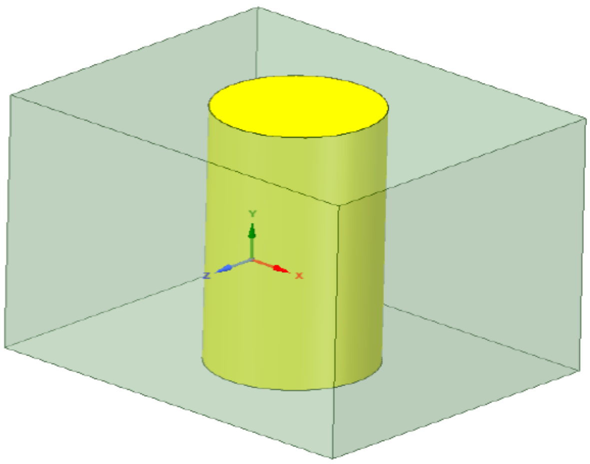

Figure 3.2: Pile foundation inside soil

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FINITE ELEMENT MESHING:

Meshing is the process of dividing the structure into smaller elements for numerical analysis. A finer mesh improves accuracy but increases computational time.

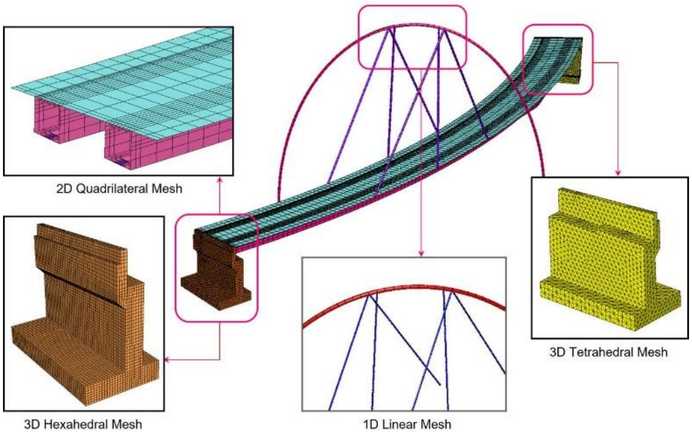

Figure 3.3: Finite Element Mesh

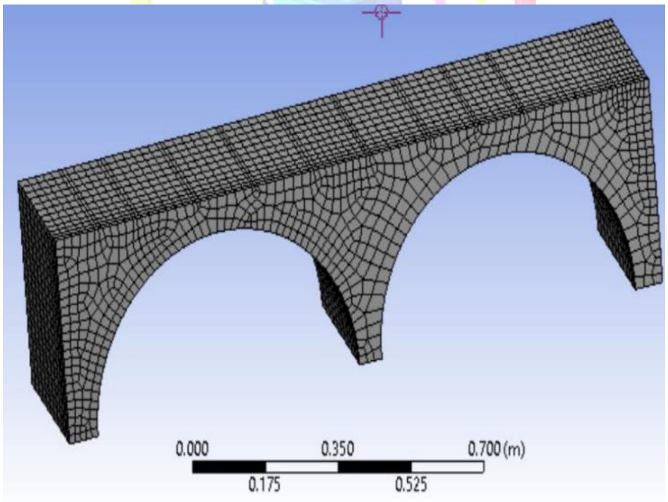

Figure 3.4: Meshed model of Bridge

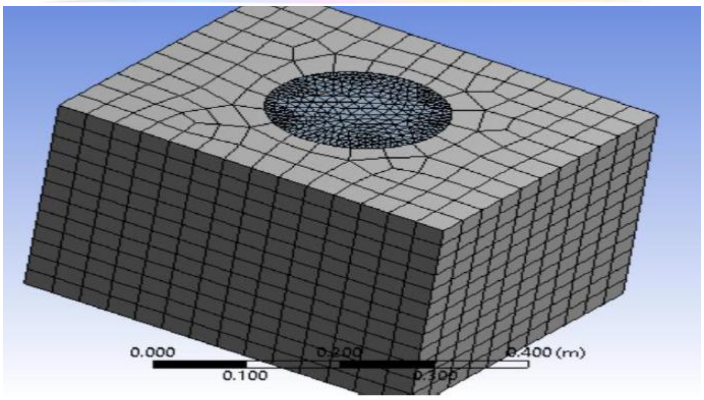

Figure 3.5: Meshed model of piles with soil

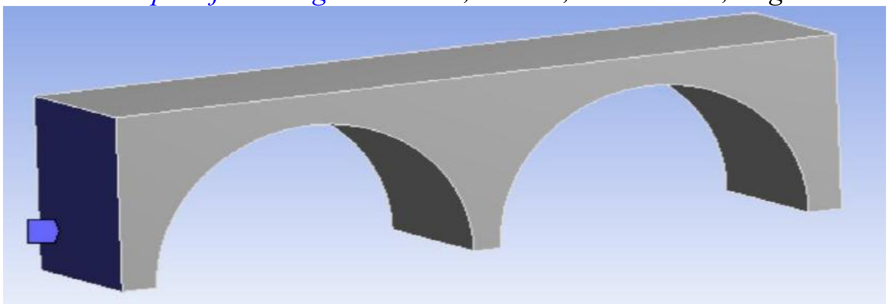

Figure 3.6: Boundary condition of Pier for simulations

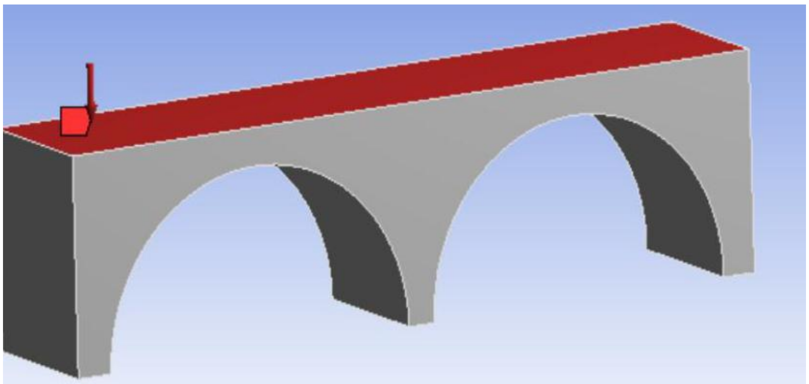

Figure 3.7: Boundary condition of Bridge for simulations

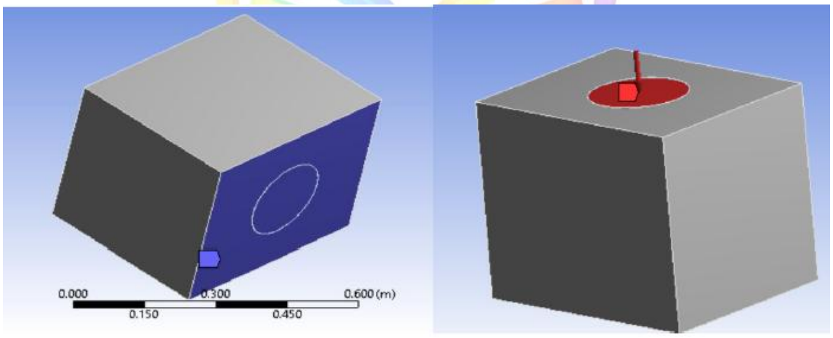

Figure 3.8: Loading conditions of pile with soil foundation

III. RESULTS AND DISCUSSION

MODES OF DEFORMATION OF BRIDGE STRUCTURE:

Under seismic loading, the bridge structure exhibits nonlinear deformation behaviour due to the dynamic nature of earthquake forces. It is observed that all bridge structures, irrespective of their geometry, start behaving nonlinearly when subjected to high-intensity seismic loads.

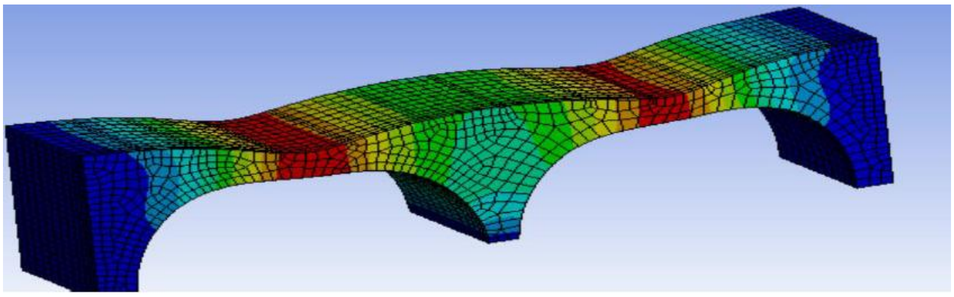

Figure 4.1: Displacement variation in Bridge structure

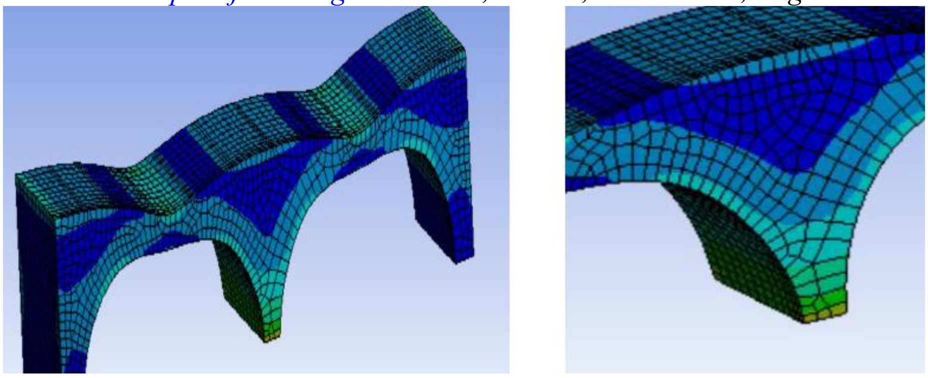

Figure 4.2: Stress variation in bridge structure

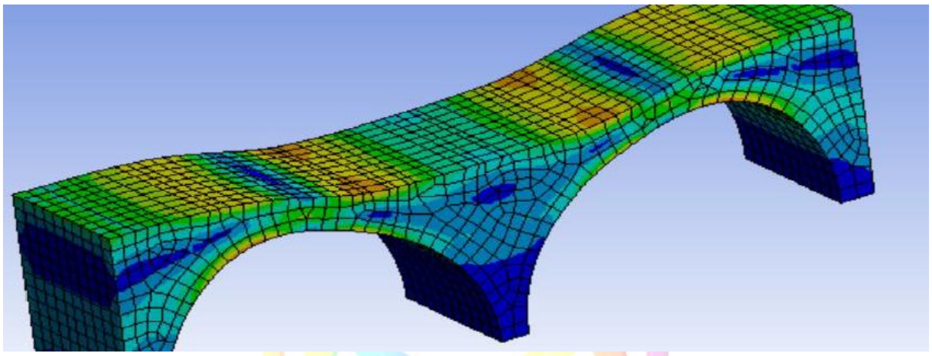

Figure 4.3: Stress variation in bridge structure of carbon fibre reinforced steel

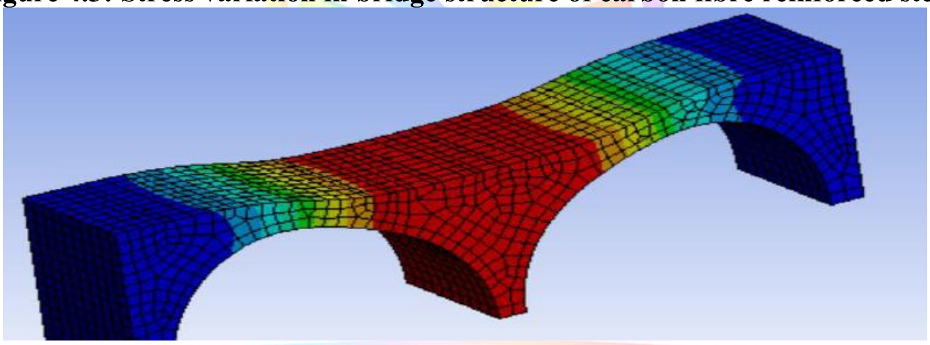

Figure 4.4: Displacement variation in carbon fibre reinforced steel Bridge structure

Discussion:

- The structure undergoes to-and-fro horizontal motion during seismic excitation.
- The magnitude of displacement increases with seismic intensity (Zone III → Zone V).
- Nonlinearity remains similar in pattern but varies in magnitude.
- Maximum deformation occurs at:
    - Mid-span of the bridge
    - Top of pier columns

It is also observed that:

- Structural steel shows maximum deformation
- Carbon fibre reinforced steel shows minimum deformation

This confirms that dynamic analysis is essential to accurately capture deformation behaviour, as static analysis cannot represent such vibration effects.

BENDING MOMENT ANALYSIS:

Bending moment is a critical parameter for structural safety. The bending moment values are analysed for all three materials under Zone III seismic loading.

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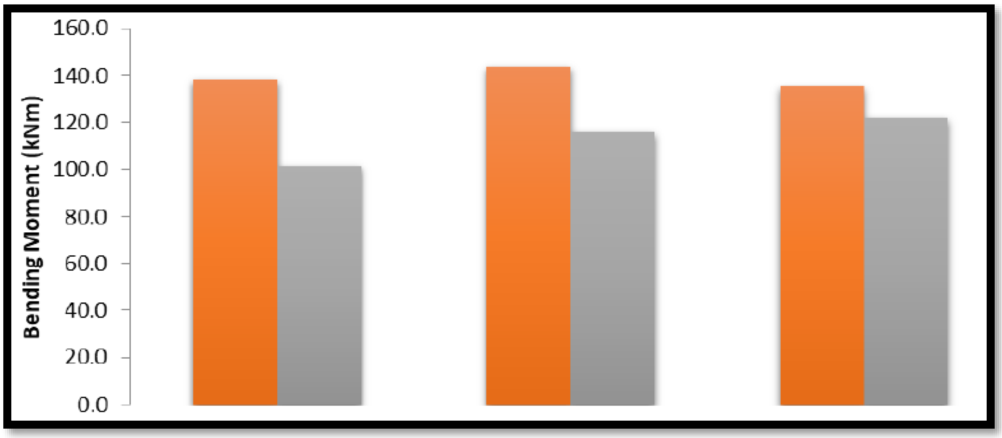

Figure 4.5: Bending moment in buildings in Zone III

Discussion:

- Maximum bending moment occurs at:
    - Pier base
    - Support regions
- Structural steel shows highest bending moment
- Carbon fibre shows lowest bending moment

This indicates that carbon fibre material has better ability to resist bending stresses, making it more suitable for seismic conditions.

SHEAR FORCE ANALYSIS:

Shear force plays an important role in the design of bridge components.

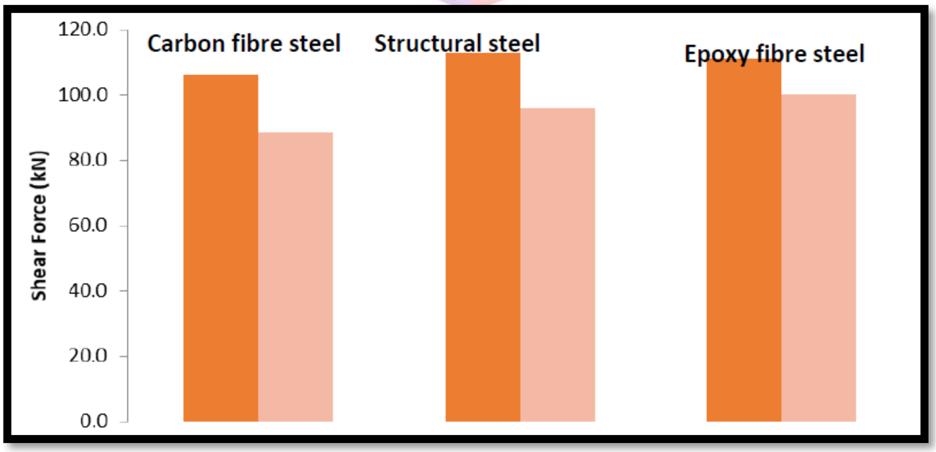

Figure 4.6: Maximum shear force in Zone III

Discussion:

- Maximum shear force is observed at support locations and foundation level
- Structural steel shows maximum shear force values
- Carbon fibre reinforced steel shows reduced shear forces

This shows that advanced materials reduce internal forces, improving structural safety.

DISPLACEMENT ANALYSIS:

Displacement is the most critical parameter in dynamic analysis.

Table 4.1: Maximum Nodal Displacement (Zone III)

Material	X-Direction (mm)	Z-Direction (mm)
Carbon Fibre Steel	63.104	63.104
Epoxy Fibre Steel	69.992	64.928
Structural Steel	70.091	70.091

Discussion:
1. Structural steel shows maximum displacement → least stable
2. Carbon fibre shows minimum displacement → most stable
3. Displacement increases with increase in seismic intensity

From the results:
1. Structural steel behaves more flexible and unstable
2. Carbon fibre behaves stiffer and more stable

Thus, carbon fibre reinforced steel significantly improves structural performance.

FACTOR OF SAFETY (FOS):

Table 4.2: Factor of Safety

Material	Factor of Safety
Structural Steel	2.1
Epoxy Fibre Steel	3.1
Carbon Fibre Steel	3.8

Discussion:
1. Carbon fibre → Highest safety
2. Structural steel → Lowest safety
3. Higher FOS means better load carrying capacity

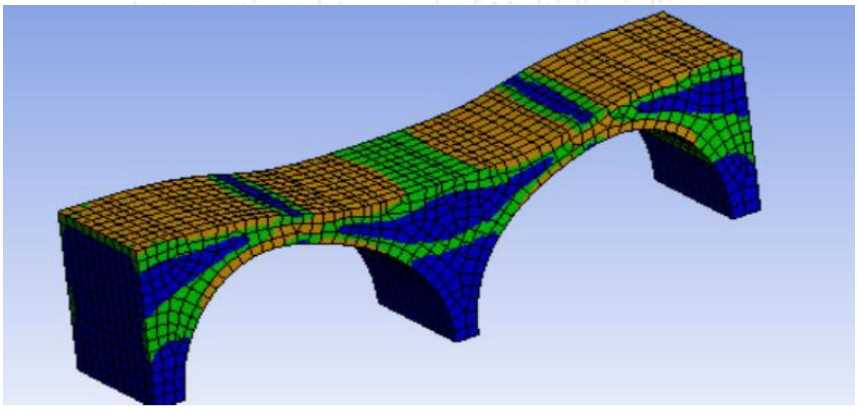

Figure 4.7: FOS pattern for Structural Steel Bridge

Figure 4.7 represents the Factor of Safety (FOS) contour pattern for the bridge structure made of structural steel when subjected to seismic loading conditions. The FOS is an important parameter that indicates the safety and reliability of the structure, defined as the ratio of the material strength to the induced stress. A higher value of FOS indicates a safer structure, while a lower value indicates a higher risk of failure. From the figure, it can be observed that the FOS distribution is not uniform throughout the bridge structure. Certain regions show lower FOS values, which are considered critical zones. These zones are generally located at:
1. Base of the pier columns
2. Beam–column junctions

3. Support regions and pile cap connections

PILE FOUNDATION WITH SOIL INTERACTION:

In the present study, a separate and detailed analysis has been carried out for the design and behaviour of pile foundation with soil interaction under the influence of seismic loading. The objective of this part of the study is to understand how the pile foundation performs when it is subjected to dynamic loads and how the surrounding soil influences its behaviour. Since pile foundations are the primary load-transferring elements in bridge structures, their performance under seismic conditions is extremely important for ensuring overall structural safety and stability.

The pile foundation system is modelled using a three-dimensional finite element approach, where both the pile and the surrounding soil are represented as interacting components. The soil is modelled as a cuboidal block of dimensions 1 m × 1 m × 1 m, which provides a simplified but effective representation of the soil medium. The pile is modelled as a cylindrical rod of 1 m length and 350 mm diameter, embedded centrally within the soil block. This configuration allows for proper simulation of soil–pile interaction behaviour under loading conditions.

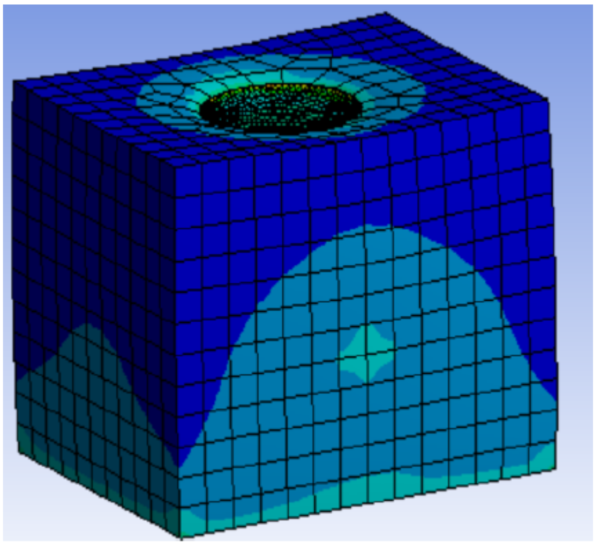

Figure 4.8: Stress pattern in piles and soil with foundation for structural steel

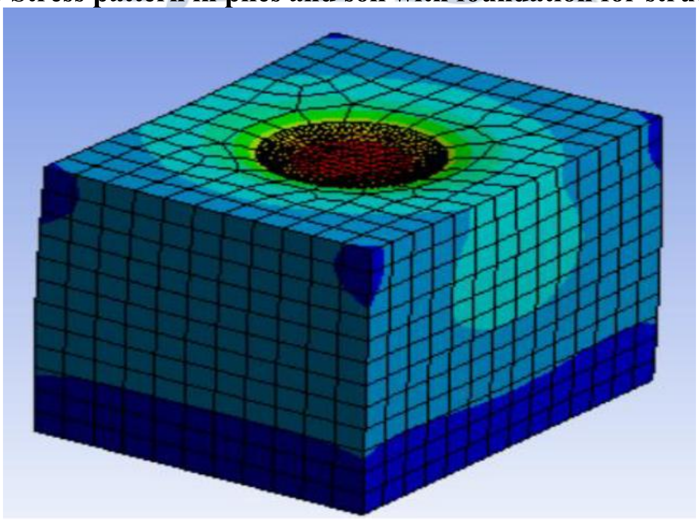

Figure 4.9: Displacement pattern in piles and soil with foundation for structural steel

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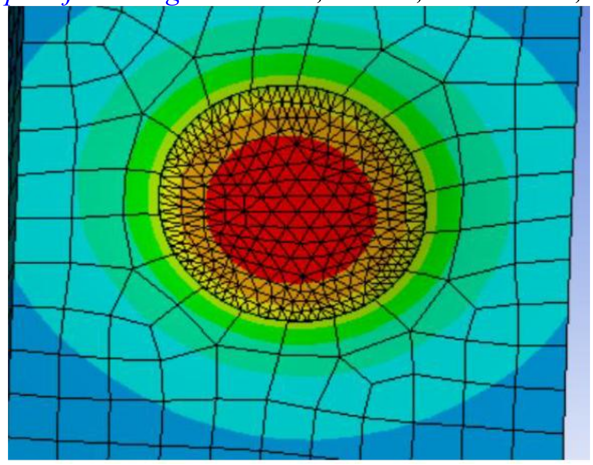

Figure 4.10: Displacement pattern in piles and soil with foundation for structural steel (Close view)

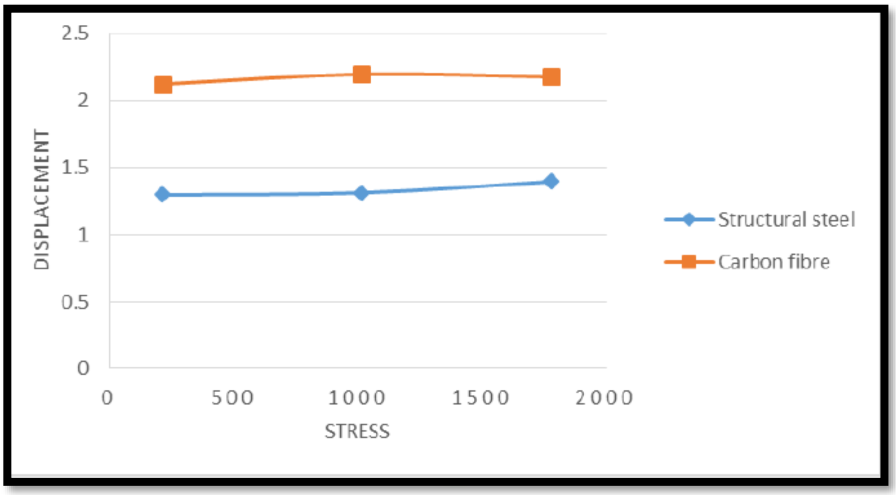

Figure 4.11: Variation between Carbon fibre reinforced steel pile and structural steel pile design

Discussion:

- Maximum stress occurs at pile–soil interface
- Soil provides damping effect, reducing vibration
- Carbon fibre piles show:
  - Less displacement
  - Better stress distribution

ENERGY ABSORPTION CHARACTERISTICS:

Energy absorption is an important parameter for seismic resistance.

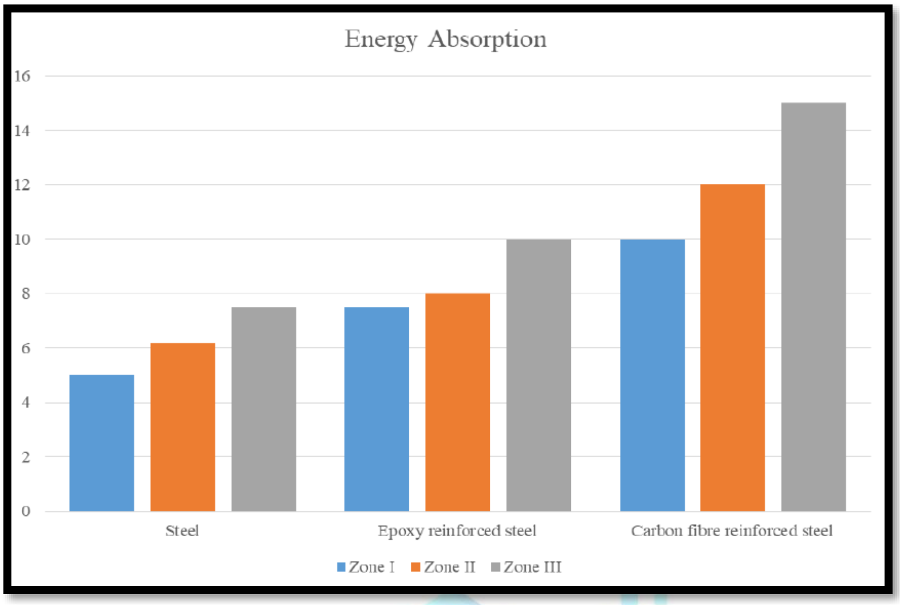

Figure 4.12: Structural performance of piles with different materials in different earthquake zones

Figure 4.13: Structural performance of piles with different materials in different earthquake zones

CONCLUSION

The present study concludes that finite element analysis is an effective and reliable method for evaluating the behavior of bridge pier pile foundations under dynamic moving loads and seismic conditions. The results clearly show that material selection plays a crucial role in structural performance, where carbon fibre reinforced steel demonstrates superior strength, stability, energy absorption, and safety compared to conventional structural steel and epoxy fibre steel. It is observed that displacement and deformation increase with seismic intensity, and soil–structure interaction significantly influences the overall response of the system. Proper modeling of dynamic loads and soil conditions is essential for accurate design. Overall, the study highlights the importance of advanced materials and detailed dynamic analysis to ensure safe, efficient, and durable bridge foundation systems under real-life loading conditions.

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