Review On Structural Performance Analysis Of Bridge Piers With Varying Geometric Shapes

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Abstract**—** The structural performance of bridge piers plays a critical role in ensuring the safety, durability, and serviceability of bridge infrastructure under varying loading conditions. This study presents a comprehensive analysis of bridge piers with different geometric shapes subjected to static, impact, and cyclic loading. Using computational simulation through ANSYS Workbench along with theoretical evaluation, the behavior of piers is examined in terms of stress distribution, deformation patterns, and fatigue performance. The analysis incorporates material properties of M35 grade concrete and steel reinforcement, along with varying load cases ranging from 850 kN to 10000 kN. Results indicate that geometric configuration significantly influences load-bearing capacity, stiffness, and resistance to failure. It is observed that piers maintain structural integrity within the elastic range up to a certain load threshold, beyond which plastic deformation and eventual failure occur. The study also highlights that steel reinforcement plays a crucial role in sustaining loads beyond concrete failure strain, thereby preventing sudden collapse. Furthermore, fatigue analysis reveals that higher loads drastically reduce the life cycle of the structure. The findings emphasize the importance of optimizing pier geometry for enhanced structural performance, improved load distribution, and long-term durability under real-world loading conditions.

Keywords: *Bridge Piers, Geometric Shapes, Structural Performance, Cyclic Loading, Stress-Strain Behavior etc.*

I. INTRODUCTION

Bridges are essential components of transportation infrastructure, enabling efficient movement of people and goods across natural and artificial obstacles. Among the various structural elements of a bridge, piers serve as the primary load-transferring components that support the superstructure and transmit loads safely to the foundation. The structural performance of bridge piers is therefore crucial for ensuring the overall stability and safety of bridge systems under different loading conditions such as dead loads, live loads, seismic forces, and vehicular impacts .

In recent years, increasing traffic loads, environmental challenges, and accidental impacts have raised concerns regarding the resilience of bridge piers. Dynamic loads such as vehicle collisions and earthquake forces introduce rapid stress variations, which may lead to significant deformation, cracking, or even structural failure. Understanding the response of bridge piers under such complex loading conditions has become a major focus of research in structural engineering [1]. Additionally, the geometric shape of bridge piers plays a vital role in determining their stiffness, load distribution characteristics, and resistance to deformation. Different shapes such as circular, rectangular, and hammerhead piers exhibit varied performance due to differences in cross-sectional properties and moment of inertia.

Previous studies have investigated the behavior of bridge piers under dynamic loading conditions. Yin et al. [1] analyzed lateral vibrations caused by vehicular loads and found that road conditions and vehicle speed significantly influence deformation patterns. Dawood et al. [2] studied the seismic performance of precast segmental piers and reported improved drift capacity and stiffness for optimized geometries. Similarly, Kwan and Billington [3] examined cyclic behavior in post-tensioned piers, highlighting reduced displacement but increased risk of concrete crushing under higher stress levels. These studies emphasize that both loading conditions and geometric configurations significantly affect structural response.

Material properties and degradation also play a crucial role in determining the long-term performance of bridge piers. Corrosion of reinforcement can reduce load-carrying capacity and structural reliability. Studies have shown that corrosion levels of up to 25% can lead to a reduction of 30–35% in strength, particularly under seismic loading conditions [5]. Furthermore, fatigue behavior under cyclic loading is a critical parameter, as repeated loading can gradually weaken the structure, leading to premature failure [11]. Advanced materials such as fiber-reinforced polymers and high-strength steel have been introduced to improve durability and performance under extreme conditions [6]–[8].

Despite significant research in this field, most studies focus either on loading conditions or material performance, with limited attention given to the influence of geometric variations on structural behavior. The interaction between geometry, material properties, and loading conditions remains an area requiring comprehensive investigation. In particular, the combined effect of impact and cyclic loading on differently shaped bridge piers is not fully explored.

The uploaded study (see Figure and methodology description on page 5–6) demonstrates the use of Finite Element Analysis (FEA) in ANSYS Workbench to evaluate pier behavior under various loading scenarios, incorporating material properties, meshing techniques, and load cases . It highlights that structural response is highly dependent on both geometry and loading intensity.

Therefore, this study aims to analyze the structural performance of bridge piers with varying geometric shapes under different loading conditions. The research focuses on evaluating stress-strain behavior, deformation patterns, and fatigue life to identify the most efficient geometric configuration. The outcomes of this study will contribute to improved design strategies for bridge piers, ensuring enhanced safety, durability, and resilience of bridge infrastructure under real-world conditions.

II. Problem Identification

- Bridge piers are continuously subjected to complex loading conditions such as dead load, live load, impact load, and cyclic loading, which may lead to structural degradation over time.
- Existing bridge designs often do not fully consider the effect of varying geometric shapes on structural performance and load distribution efficiency.
- Dynamic forces such as vehicular collisions and seismic activities generate sudden stress concentrations, increasing the risk of cracking and failure.
- Many studies focus on material strength and reinforcement but neglect the influence of pier geometry on stiffness, deformation, and fatigue behavior.
- Inadequate understanding of stress-strain behavior under high loads can result in unsafe designs and reduced service life of bridge piers.
- Fatigue failure due to repeated cyclic loading remains a critical issue, especially when load exceeds the elastic limit.
- Limited integration of computational tools like FEM for analyzing real-world loading scenarios leads to less accurate predictions of structural performance.
- There is a need to optimize geometric configurations to enhance strength, durability, and safety of bridge piers.

III. Scope of Study

This study focuses on evaluating the structural performance of bridge piers with varying geometric shapes under different loading conditions. It includes analysis of stress, strain, deformation, and fatigue behavior using computational tools such as Finite Element Method (FEM) in ANSYS Workbench. The study considers M35 grade concrete and steel reinforcement to simulate real-world material behavior. Various load cases, including static, impact, and cyclic loading, are applied to assess the response of different pier geometries.

The scope also involves comparing the efficiency of geometric configurations in terms of load-bearing capacity, stiffness, and durability. It aims to identify the most suitable pier shape for improved structural performance and safety. Additionally, the study provides insights for optimizing design parameters and enhancing the resilience of bridge piers against dynamic forces such as vehicular impact and seismic loads.

IV. Literature Reviews

A) *Literature Survey:*

1. Singh et al., 2025, Singh et al. (2025) conducted a comprehensive study on bridge piers subjected to impact and cyclic loading using experimental and computational approaches. The research highlighted that bridge piers can safely withstand loads up to design limits but experience rapid failure beyond critical thresholds. The study emphasized the importance of stress-strain behavior, showing that concrete fails at a strain of 0.0035, after which load transfer occurs to steel reinforcement. Fatigue analysis revealed that life cycles significantly reduce with increasing load, especially beyond 1500 kN. The authors concluded that proper reinforcement design and load management are essential for improving structural resilience and preventing catastrophic failure in bridge piers.

2. Guo et al., 2024, investigated the performance of prefabricated concrete-filled steel tube (CFST) bridge piers under seismic loading. The study demonstrated that hybrid composite piers offer improved stiffness, ductility, and energy dissipation compared to conventional reinforced concrete piers. Finite element analysis results showed reduced lateral displacement and better load distribution in optimized geometries. The authors emphasized the importance of combining steel and concrete for enhanced structural performance. Additionally, the study suggested that prefabrication techniques improve construction efficiency and reduce maintenance requirements. The findings support the use of innovative composite designs for achieving better seismic resistance and long-term durability in modern bridge infrastructure.

3. Luo et al., 2024, developed a sonar-based 3D reconstruction system for monitoring underwater bridge piers. The study highlighted the importance of advanced inspection techniques for detecting structural damage and geometric irregularities. The findings showed that accurate 3D models help in assessing stress concentration zones and predicting potential failure regions. The research emphasized that real-time monitoring improves maintenance planning and enhances structural safety. The authors concluded that integrating digital technologies with structural analysis can significantly improve the lifespan and reliability of bridge piers, especially in harsh environmental conditions where traditional inspection methods are limited.

4. Moussa et al., 2024, explored self-centering precast bridge piers incorporating fiber-reinforced polymers and energy dissipation systems. The study found that such systems effectively reduce residual displacement after seismic events, improving structural recovery. Experimental results indicated that these piers exhibit enhanced durability and reduced maintenance requirements. The authors also observed that innovative materials improve resistance against cyclic loading and fatigue damage. The research concluded that adopting smart materials and self-centering mechanisms can significantly enhance bridge safety and resilience, particularly in earthquake-prone regions.

5. Li et al., 2024, studied the behavior of bridge piers strengthened with basalt fiber-reinforced polymer (BFRP) under seismic loading. The results showed that BFRP significantly enhances load-carrying capacity and reduces crack propagation. The study highlighted that strengthened piers exhibit improved ductility and energy absorption capacity. The authors emphasized the role of advanced materials in mitigating structural damage during

earthquakes. Additionally, the research demonstrated that BFRP reinforcement leads to better performance compared to traditional steel reinforcement in terms of corrosion resistance and durability. The findings support the use of fiber-reinforced materials for improving long-term performance of bridge structures.

6. Yuan et al., 2023, investigated the effect of corrosion and cyclic loading on reinforced concrete bridge piers. The study revealed that corrosion significantly reduces yield strength and ultimate load capacity. Results indicated that a 25% corrosion level can reduce structural strength by up to 35%. The research also showed that cyclic loading accelerates material degradation and reduces fatigue life. The authors concluded that corrosion combined with dynamic loading poses a major threat to bridge durability. Proper maintenance strategies and corrosion-resistant materials are necessary to enhance structural longevity and ensure safety in bridge infrastructure.

7. Zhang et al., 2024, analyzed the seismic performance of segmental precast bridge piers with hybrid connections. The study found that such piers exhibit higher drift capacity and improved energy dissipation compared to traditional monolithic piers. Finite element analysis revealed that reducing aspect ratio increases stiffness and load-bearing capacity. The research also highlighted the importance of joint behavior in determining overall structural performance. The authors concluded that optimized geometric design and connection detailing play a crucial role in enhancing seismic resilience and reducing structural damage during earthquakes.

8. Szerszen and Jarzab, 2021, performed a fatigue reliability analysis of bridge piers under cyclic loading conditions. The study showed that fatigue significantly affects structural safety, especially in piers with lower reinforcement ratios. The reliability index decreases as cyclic loading increases, indicating higher failure probability. The research emphasized that both material properties and geometric parameters influence fatigue performance. The authors recommended incorporating fatigue analysis in bridge design codes to ensure long-term safety and durability. The findings highlight the importance of considering cyclic loading effects in structural design and maintenance planning.

9. Zhou and Zhang, 2020, studied the development of modern bridge technologies with a focus on structural efficiency and cost reduction. The research highlighted the advantages of integral bridge systems, which eliminate joints and bearings, improving durability and seismic performance. The authors emphasized that optimized structural design, including pier geometry, plays a vital role in enhancing load distribution and reducing maintenance costs. The study concluded that adopting innovative construction techniques and materials can significantly improve the performance and lifespan of bridge infrastructure.

10. Tazarv et al., 2021, reviewed the behavior of precast bridge columns with grouted duct connections under seismic loading. The study found that such systems provide improved constructability and adequate strength performance. Experimental results indicated that connection detailing significantly affects energy dissipation and ductility. The authors highlighted that proper design of joints enhances structural integrity and reduces failure risk. The research concluded that precast systems with optimized connections are a promising solution for modern bridge construction, offering both structural efficiency and reduced construction time.

B) Literature Summary

Recent studies on bridge piers highlight the importance of structural performance under dynamic loading conditions such as seismic forces, vehicular impacts, and cyclic loading. Researchers have extensively analyzed stress-strain behavior, deformation patterns, and fatigue life using experimental and computational methods. Advanced materials like fiber-reinforced polymers and composite sections have been introduced to enhance durability, ductility, and corrosion resistance. Several studies emphasize that reinforcement plays a critical role in maintaining structural integrity beyond concrete failure limits. Additionally, innovations in prefabrication and self-centering mechanisms have improved seismic resilience and reduced maintenance requirements. However, most research primarily focuses on material properties, loading effects, or reinforcement techniques. The integration of computational tools like FEM has improved analysis accuracy, enabling better prediction of structural behavior under real-world conditions. Overall, existing literature contributes significantly to improving bridge pier design, safety, and long-term performance.

C) Research Gap

Despite extensive research on bridge piers, several critical gaps remain unaddressed. Most studies focus on either loading conditions or material enhancements, with limited attention given to the influence of varying geometric shapes on structural performance. The combined effect of geometric configuration, material behavior, and dynamic loading conditions such as impact and cyclic loads is not thoroughly explored. Additionally, there is insufficient comparative analysis of different pier shapes in terms of stress distribution, stiffness, and fatigue life. Existing research also lacks integration of real-world loading scenarios with advanced computational modeling techniques for accurate prediction. Furthermore, the interaction between concrete and steel under extreme loading conditions requires deeper investigation. There is a need to develop optimized geometric designs that improve load-bearing capacity, reduce stress concentration, and enhance durability. Addressing these gaps will contribute to safer, more efficient, and resilient bridge infrastructure design.

V. RESEARCH METHODOLOGY

A) Criteria for selecting this study:

- The study is selected based on its relevance to structural engineering, particularly focusing on bridge pier performance under varying geometric shapes and loading conditions.
- It addresses real-world challenges such as impact loading, cyclic loading, and seismic forces, which are critical for modern infrastructure safety and durability.
- The availability of experimental, theoretical, and computational data makes the study comprehensive and suitable for in-depth analysis.
- The use of Finite Element Method (FEM) tools like ANSYS ensures accurate simulation of structural behavior under complex loading scenarios.
- The study includes detailed parameters such as stress-strain behavior, deformation patterns, and fatigue life, which are essential for performance evaluation.

- It considers practical materials like M35 concrete and steel reinforcement, making the findings applicable to real construction practices.
- The research also provides scope for comparative analysis of different geometric configurations.
- The study contributes to improving design strategies, enhancing safety, and optimizing structural efficiency of bridge piers.

B) Method of Analysis

- The study adopts a computational approach using Finite Element Method (FEM) implemented in ANSYS Workbench for structural analysis.
- Initially, the geometric models of bridge piers with varying shapes are developed, considering dimensions and structural configurations.
- Material properties such as density, Young's modulus, and Poisson's ratio for concrete and steel are defined accurately.
- Meshing is performed to divide the structure into finite elements, ensuring precise stress and deformation analysis.
- Boundary conditions and load cases, including static, impact, and cyclic loading, are applied to simulate real-world conditions.
- Static structural analysis is carried out to understand the basic response of the pier under steady loads.
- Dynamic analysis evaluates the behavior under varying loads, including fatigue and cyclic effects.
- The results are analyzed in terms of stress distribution, strain values, deformation, and fatigue life.
- Comparative evaluation is performed for different geometric shapes to identify the most efficient configuration.
- Validation of results is done by comparing simulation outputs with theoretical or experimental findings.

C) Evaluation of Methodologies Used in Reviewed Studies

- Most reviewed studies utilize experimental, analytical, and computational approaches to evaluate bridge pier performance.
- Finite Element Analysis (FEA) is widely used due to its accuracy in predicting stress, strain, and deformation behavior.
- Experimental methods provide real-time validation but are often time-consuming and costly.
- Analytical methods offer simplified solutions but may not capture complex loading conditions effectively.
- Many studies integrate hybrid approaches combining experimental and numerical methods for better accuracy.
- Advanced tools like ANSYS, ABAQUS, and MATLAB are commonly used for simulation and analysis.
- Some studies focus on material enhancement techniques such as fiber reinforcement and composite structures.
- Methodologies involving fatigue analysis and cyclic loading evaluation are gaining importance for durability assessment.
- However, limited studies consider the combined effect of geometry, material, and dynamic loading simultaneously.
- Overall, modern methodologies are shifting towards computational modeling with validation to improve accuracy and efficiency.

D) Highlighting trends, advancements, and challenges

Trends :

- Increasing use of FEM-based simulation tools
- Adoption of advanced composite materials
- Focus on seismic and dynamic analysis
- Integration of digital monitoring systems
- Emphasis on durability and fatigue analysis

Advancements :

- Development of self-centering bridge piers
- Use of fiber-reinforced polymers (FRP)
- Improved computational modeling accuracy
- Adoption of prefabrication techniques
- Enhanced fatigue and life-cycle prediction methods

Challenges :

- Limited consideration of geometric variations
- High computational cost for complex models
- Difficulty in simulating real-world conditions
- Material degradation issues like corrosion
- Lack of standardized design guidelines for advanced systems.

VI. Discussion

A) Methodology for future research directions

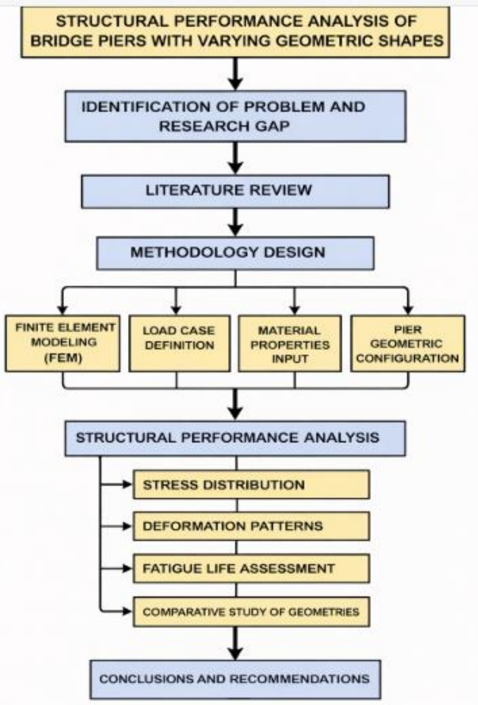

Figure 1. Bridge pier performance analysis flowchart

- The working principle of this study is based on analyzing the structural behavior of bridge piers with varying geometric shapes under different loading conditions using computational simulation techniques.
- Initially, the geometric models of different pier shapes (rectangular, circular, hammerhead, etc.) are created to study their structural response.
- Material properties such as M35 grade concrete and steel reinforcement are defined to replicate real-world construction conditions.
- The models are then imported into Finite Element Method (FEM)-based software like ANSYS Workbench for analysis.
- Meshing is performed to divide the structure into small finite elements for accurate stress and deformation calculations.

- Boundary conditions and constraints are applied to simulate real support conditions of bridge piers.
- Different load cases such as static load, impact load, and cyclic load are applied to evaluate performance.
- The system computes stress, strain, and deformation values under each loading condition.
- The transition from elastic to plastic behavior is analyzed to determine failure limits.
- Fatigue analysis is conducted to evaluate the life cycle under repeated loading.
- Comparative analysis of results helps identify the most efficient geometric shape for strength, durability, and safety.

This study aims to evaluate the structural performance of a hammerhead pier under varying impact loading and cyclic stress conditions using ANSYS Workbench:

- ANSYS Workbench Setup
  - The initial setup in ANSYS Workbench, a tool for static structural analysis, defines the framework for simulating real-world conditions.
  - This stage involves applying complex loads, boundary conditions, and material properties systematically.
- Static Structural Analysis
  - After model setup, static structural analysis determines the structure's response to static (non- changing) loads, forming the basis for dynamic loading conditions.
  - Understanding static behavior is essential before simulating complex impact or cyclic loads, as it provides a foundation for assessing material performance under steady-state conditions.
- Engineering Properties
  - Material properties such as density, Young's modulus, and Poisson's ratio for concrete (M35) and steel are inputted, as detailed in Table 1.
  - Accurate material behavior representation ensures results reflect real-world structural performance.
  - Specifying strain life parameters (Table 2) accurately captures cyclic loading effects, crucial for simulating long-term wear.
- Geometrical Properties
  - Geometrical properties, including dimensions and moments of inertia, are added (Table 3), directly influencing stiffness, load distribution, and deformation behavior.
  - This step ensures the physical characteristics of the pier are precisely captured in the simulation, aligning with study objectives.
- Model Creation
  - With material and geometrical properties defined, the hammerhead pier model is created, including its foundation and connections to the bridge superstructure.
  - The model serves as the basis for simulating the dynamic response under different loading conditions.
- Meshing
  - Meshing is essential in finite element analysis (FEA) as it divides the pier structure into smaller elements for detailed analysis.
  - The mesh size impacts the result accuracy and is adjusted for the required precision. Fine meshing was employed to capture detailed stress distribution and deformation under impact and cyclic loading.
  - Various mesh types, such as hexahedral and tetrahedral, were used based on structural complexity.
  - High-quality meshing ensures an accurate representation of localized stress concentrations and strain behaviors.
- Results Generation
  - After meshing and defining properties, loading conditions (Table 4) are applied, and the analysis is executed.
  - The results provide insights into the hammerhead pier's structural performance, including stress concentration, deformation, and load-bearing capacity.
  - This step is crucial for understanding the structure's behavior under impact and cyclic loads, aligning with the study's objectives.
- Matching Experimental Data
  - Simulation data is compared with experimental or real-world data (if available) to verify accuracy.
  - Discrepancies lead to model adjustments and rerunning the analysis to ensure alignment with expected outcomes.
  - This iterative process is vital for validating the model's accuracy and reliability of findings.
- Final Validation
  - Once simulation results align with experimental data and meet study objectives, the analysis is complete.
  - The findings are then used to recommend improvements for the structural resilience of hammerhead piers under various loading scenarios.

Table 1: Material Properties

Property	**Concrete (M35)**	**Steel**
Density (kg/m³)	2300	—
Coefficient of Thermal Expansion	1.40×10^{-5}	—
Young's Modulus (Pa)	3.00×10^{10}	—
Poisson's Ratio	0.18	—
Shear Modulus (Pa)	1.27×10^{10}	—
Bulk Modulus (Pa)	1.56×10^{10}	—
Tensile Ultimate Strength (Pa)	4.14×10^{6}	—
Compressive Strength (MPa)	35	—
Tensile Strength (MPa)	—	415

- This table defines the mechanical and physical properties of M35 concrete and steel used in the bridge pier model.
- Density (2300 kg/m³) represents the self-weight of concrete, influencing dead load calculations.
- Young's modulus (3.00×10^{10} Pa) indicates stiffness and resistance to deformation under load.
- Poisson's ratio (0.18) shows the lateral strain behavior when axial load is applied.
- Shear and bulk modulus represent resistance to shear and volumetric deformation.
- Thermal expansion coefficient defines behavior under temperature variations.
- Compressive strength (35 MPa) is critical for load-bearing capacity of concrete.

- Tensile strength of steel (415 MPa) highlights its role in resisting tensile forces.
- Concrete has low tensile strength, hence steel reinforcement is essential.
- These properties are used as input parameters in FEM analysis.
- Accurate material definition ensures realistic simulation results and structural behavior prediction.

Table 2: Strain Life Parameters of Concrete (M35)

Parameter	Value
Strength Coefficient (Pa)	5.00×10^8
Strength Exponent	-0.15
Ductility Coefficient	0.2
Ductility Exponent	-0.6
Cyclic Strain Hardening Exponent	0.23

- This table represents fatigue and cyclic loading behavior of M35 concrete.
- Strength coefficient (5.00×10^8 Pa) indicates the stress level at failure under cyclic loading.
- Strength exponent (-0.15) defines the rate at which material strength reduces under repeated loading.
- Ductility coefficient (0.2) represents the ability of concrete to undergo plastic deformation.
- Ductility exponent (-0.6) shows how ductility decreases with increasing cycles.
- Cyclic strain hardening exponent (0.23) indicates material hardening under repeated stress.
- These parameters help in predicting fatigue life of the structure.
- They are essential for analyzing long-term durability of bridge piers.
- Used in fatigue models within FEM software like ANSYS.
- Helps identify failure conditions under repeated loading.
- Ensures safe design against cyclic loads such as traffic and seismic forces.

Table 3: Geometrical Properties of Hammerhead Pier.

Property	Value
Length X (m)	11.5
Length Y (m)	2
Length Z (m)	7.3
Volume (m^3)	19.43
Mass (kg)	44,689
Centroid X (m)	5.73
Centroid Y (m)	0.5
Centroid Z (m)	1.597
Moment of Inertia IP1	3.80×10^5
Moment of Inertia IP2	1.23×10^6
Moment of Inertia IP3	8.71×10^5

- This table defines the physical dimensions and shape characteristics of the hammerhead pier.
- Lengths (X, Y, Z) determine overall size and structural configuration.
- Volume (19.43 m^3) helps calculate material quantity and weight.
- Mass (44,689 kg) contributes to dead load acting on the structure.
- Centroid coordinates define the center of gravity for stability analysis.
- Moment of inertia values (IP1, IP2, IP3) indicate resistance to bending in different directions.
- Higher inertia means greater resistance to deformation.
- Geometry directly affects stiffness, load distribution, and stress concentration.
- Accurate modeling ensures realistic simulation of structural behavior.
- These parameters are essential inputs for FEM analysis.
- Helps compare performance of different geometric shapes

Table 4: Load and moment cases as applied in the analysis on piers.

Load Case	Load (kN)	Moment Case	Moment (kN·m)
1	850	1	850
2	1000	2	1000
3	2000	—	—
4	5000	—	—
5	10000	—	—

- This table represents different loading scenarios applied to the bridge pier.
- Load cases (850 kN to 10000 kN) simulate real-world conditions such as traffic and impact loads.
- Loads are applied at specific points (B, C, D, F) to analyze stress distribution.
- Moment cases (850 and 1000 kN·m) represent bending effects on the pier.
- Helps evaluate structural response under combined loading conditions.
- Lower loads represent normal operating conditions.
- Higher loads simulate extreme conditions such as collisions or seismic events.
- Used to identify elastic, plastic, and failure regions of the structure.
- Important for assessing safety and load-bearing capacity.
- Helps determine critical load limits beyond which failure occurs.
- Essential for designing safe and durable bridge piers under varying conditions.

These parameters define the structural model used for analysis. Material properties determine strength behavior, strain life parameters evaluate fatigue performance, geometrical properties influence stiffness and load distribution, and loading cases simulate real-world conditions for performance assessment.

VII. CONCLUSION

This review paper presents a comprehensive analysis of the structural performance of bridge piers with varying geometric shapes under different loading conditions. The study highlights that geometric configuration plays a significant role in influencing stiffness, load distribution, deformation behavior, and overall structural stability. From the reviewed literature, it is evident that while material properties and reinforcement techniques have been extensively studied, the impact of pier geometry remains comparatively underexplored.

The findings indicate that bridge piers perform effectively within the elastic range under design loads; however, exceeding critical load limits leads to plastic deformation and eventual failure. The role of steel reinforcement is crucial in maintaining structural integrity beyond the failure strain of concrete. Additionally, fatigue analysis reveals that repeated cyclic loading significantly reduces the lifespan of bridge piers, especially under high load conditions.

Advancements in computational tools such as FEM have improved the accuracy of structural analysis, enabling better prediction of performance. Overall, optimizing geometric design along with material selection and loading considerations is essential for developing safe, durable, and efficient bridge pier structures.

REFERENCES

[1] S. D. Singh, D.-P. N. Kontoni, P. Anand, and S. K. Yadav, "Evaluating the structural integrity of bridge piers under impact and cyclic loading: A computational and experimental approach," *Eccomas Proceedia COMPDYN*, vol. 4999–5015, 2025.

[2] A. Guo, W. Yuan, H. Li, and H. Li, "Structural strength deterioration of coastal bridge piers considering non-uniform corrosion in marine environments," *Earthquake Engineering and Engineering Vibration*, vol. 17, pp. 429–444, 2024.

[3] J. Luo, S. Jiang, Y. Zeng, and C. Lai, "Three-dimensional reconstruction and visualization of underwater bridge piers using sonar imaging," *Sensors*, vol. 24, no. 14, 2024.

[4] A. M. Moussa, M. F. Fahmy, F. Niu, X. Wang, and Z. Wu, "Self-centering precast unit as energy dissipation members in precast segmental bridge columns," *Buildings*, vol. 14, no. 2, 2024.

[5] C. Li, Y. Peng, P. Yang, H. Zhou, and N. Wang, "Behavior of a precast bridge pier with basalt fiber-reinforced polymer (BFRP)-strengthened segments under seismic loading," *Polymers*, vol. 16, no. 14, 2024.

[6] W. Yuan, Y. Wang, P. Zhou, and Y. Yao, "Effect of biaxial loading path on seismic performance of RC bridge piers with corrosion damage," *KSCE Journal of Civil Engineering*, vol. 27, no. 12, pp. 5243–5255, 2023.

[7] R. Zhang, L. Zheng, H. Zhong, and S. Qin, "Seismic behavior of assembled concrete bridge piers with hybrid joint connections," *Structures*, 2024.

[8] M. M. Szerszen and M. Jarzab, "Fatigue reliability of hammerhead bridge piers," *Journal of Bridge Engineering*, vol. 19, no. 3, 2021.

[9] X. Zhou and X. Zhang, "Thoughts on the development of bridge technology in China," *Engineering*, vol. 5, no. 6, pp. 1120–1130, 2020.

[10] M. Tazarv, G. Shrestha, and M. S. Saiidi, "State-of-the-art review and design of grouted duct connections for precast bridge columns," *Structures*, vol. 30, pp. 895–909, 2021

[10] C. Li, Y. Peng, P. Yang, H. Zhou, and N. Wang, "Behavior of a Precast Bridge Pier with Basalt Fiber-Reinforced Polymer (BFRP)-Strengthened Segments under Seismic Loading," Polymers, vol. 16, no. 14, article no. 2018, 2024.

[11] M. M. Szerszen and M. Jarzab, "Fatigue Reliability of Hammerhead Bridge Piers," J. Bridge Eng., vol. 19, no. 3, article no. 04013006, Mar. 2014.

[12] AASHTO, "LRFD Bridge Design Specifications (Customary U.S. Units), 6th ed.," American Association of State Highway and Transportation Officials, Washington, DC, 2012.

[13] R. Zhang, L. Zheng, H. Zhong, and S. Qin, "Seismic behavior of assembled concrete bridge piers with hybrid joint connections," 2024.