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Performance-Based Seismic Analysis Of Bridge Piers: A Study In Concrete Technology

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Abstract
Seismic analysis is the process of evaluating the response of structures to seismic activity, ensuring their safety and functionality during and after earthquakes. This study addresses the limitations of traditional seismic analysis methods and emphasizes the necessity for performance-based approaches to better capture realistic seismic scenarios. The objectives of this research are to conduct a performance-based seismic analysis of bridge piers utilizing modern concrete technologies, such as high-performance and fibre-reinforced concrete, and to develop guidelines for their implementation in seismic regions. The study employs quasi-static cyclic loading and dynamic shake table tests to evaluate the seismic performance of bridge piers constructed with high-strength concrete, steel reinforcement, and Shape Memory Alloy (SMA). The proposed model integrates SMA with traditional materials to enhance energy dissipation and minimize residual deformations. The experimental methodology includes specimen preparation, seismic testing, instrumentation, data analysis, and finite element modeling. Results indicate that SMA-reinforced piers exhibit improved performance, with SMA stress reaching 442.5 MPa at a 0.005 strain and steel yielding stress at 525 MPa. The proposed model demonstrates significant enhancements in seismic performance, providing a robust framework for performance-based seismic analysis of bridge piers and highlighting the critical role of advanced materials in achieving resilient infrastructure.

Keywords: Seismic analysis, High-strength concrete, Shape Memory Alloy (SMA), Quasi-static cyclic loading, Dynamic shake table tests.

1. Introduction

Seismic analysis is the process of evaluating the response of structures, such as buildings and bridges, to seismic activity. This involves assessing how these structures behave during and after an earthquake, considering factors such as ground motion, structural dynamics, and material properties [1]. Seismic analysis plays a crucial role in the design and construction of bridge piers, ensuring they can withstand earthquake-induced forces [2]. Traditional seismic analysis methods often face challenges such as oversimplification of seismic demands and inadequate consideration of actual structural performance under seismic events [3]. These limitations underscore the necessity for performance-based approaches, which focus on the anticipated behavior of structures under realistic seismic scenarios [4]. Recent advancements in concrete technology, such as high-performance and fibre-reinforced concrete, offer significant potential to enhance the seismic performance of bridge piers by improving their strength, ductility, and energy absorption capabilities [5].

This research aims to conduct a performance-based seismic analysis of bridge piers utilizing modern concrete technologies. By doing so, it seeks to bridge the gap between conventional design practices and the latest innovations in material science, providing a more reliable and resilient design framework for bridge infrastructure [6]. The scope of this study includes evaluating the seismic response of bridge piers with advanced concrete materials and developing guidelines for their implementation in seismic regions. This research is significant because it has the potential to enhance the safety and longevity of bridges, hence enhancing the overall resilience of transportation networks [7]. Tentative contributions include the development of new analytical models, experimental validation of materials, and design recommendations for engineers [8].

1.1 Seismic Analysis

Seismic analysis is a crucial discipline in structural engineering, focused on understanding and predicting how buildings and infrastructure respond to earthquakes and other seismic events. Earthquakes produce seismic waves that travel through the Earth's crust, resulting in ground movement that can exert forces on structures [9]. The waves mentioned consist of P-waves, which are rapid compressional waves, and S-waves, which are shear waves that induce shaking perpendicular to the direction of P-waves [10]. Additionally, surface waves such as Love and Rayleigh waves can cause significant ground displacements. Engineers employ various methods to analyze the seismic performance of structures [11]. Response spectrum analysis assesses the highest level of response that a structure can experience by analyzing a range of ground motion data. Time-history analysis is a method that accurately evaluates the dynamic reaction of structures by simulating the complete time history of ground motion. Pushover analysis evaluates the capacity of structures to withstand increasing levels of lateral force until collapse mechanisms or excessive deformation occur [12].

By conducting seismic analysis, engineers can design structures that mitigate potential damage, ensuring safety and resilience in earthquake-prone regions. Building codes and regulations incorporate findings from seismic analysis to establish minimum design criteria, further enhancing the earthquake resistance of structures worldwide [13].

1.2 Classification of Seismic Analysis Methods

Seismic vulnerability assessment methods can be categorized into empirical, hybrid, and analytical approaches, each offering unique advantages and applications. Empirical methods (EM) use past data and patterns of damage to guess how structures react to earthquakes. They provide the ability to use statistical analysis to determine a structure's vulnerability level [14]. Hybrid methods (HM) integrate elements of both empirical and analytical approaches, aiming to enhance the accuracy and reliability of predictions by leveraging the strengths of each method [15]. Analytical methods are further divided into detailed analytical methods (DAM) and simplified analytical methods (SAM) approaches [16]. Detailed analytical methods encompass techniques such as collapse mechanism-based (CMB) analysis, which focuses on identifying and modeling potential failure mechanisms of structures under seismic loads. Simplified analytical methods include capacity spectrum-based (CSB) approaches, which evaluate seismic performance by comparing structural capacity with seismic demand, and fully displacement-based (FDB) methods, which directly assess the displacement demands and capacities of structures during seismic events [17][18]. Figure 1 shows the classification framework, which provides a comprehensive understanding of the different methodologies available for seismic vulnerability assessment, empowering engineers to choose the most appropriate method by considering the unique demands and constraints of their projects.

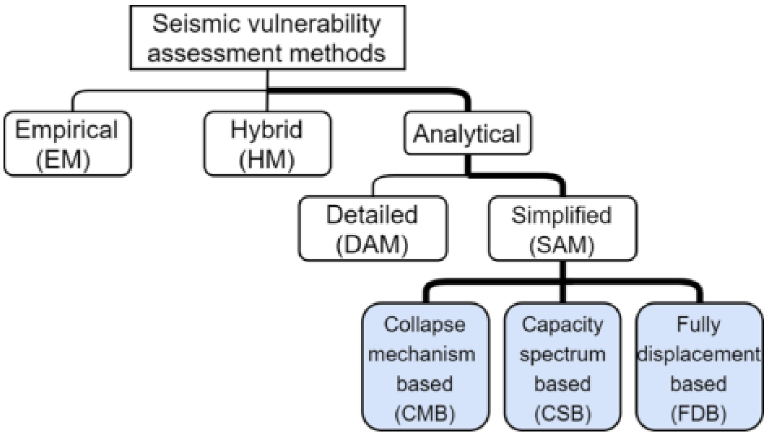

Figure 1. Seismic vulnerability assessment methods classification [19].

1.3 Challenges in Traditional Seismic Analysis Methods

Traditional seismic analysis methods face several challenges in accurately predicting and mitigating structural responses to earthquakes. One significant challenge is the complexity of ground motion prediction. Seismic waves exhibit significant variations in amplitude, frequency content, and duration, which are influenced by factors such as earthquake magnitude, distance from the point of origin, and local geological conditions [20]. Traditional methods often rely on simplified models or assumptions about ground motion, which might not capture the full spectrum of possible earthquake scenarios accurately [21]. Another challenge lies in the complexity of structural behavior under seismic loads. Buildings and infrastructure exhibit nonlinear behavior when subjected to large seismic forces, including stiffness degradation, strength deterioration, and potential collapse mechanisms [22]. Traditional methods like response spectrum analysis or simplified linear elastic models might not adequately capture these nonlinear effects, leading to conservative or overly optimistic predictions of structural performance [23].

Addressing these challenges requires advancements in computational tools, experimental testing techniques, and interdisciplinary collaboration among geotechnical engineers, structural engineers, and seismologists [24]. Integrating advanced modeling approaches, such as performance-based design and probabilistic methods, can enhance the reliability of seismic analyses by better capturing the complex interactions between ground motion and structural response, ultimately improving the resilience of built environments against seismic hazards [25].

This research significantly contributes to the field by developing analytical models for performance-based seismic analysis of bridge piers using high-performance and fibre-reinforced concrete. It includes experimental validation of the materials under seismic conditions, generating data to support the models and demonstrate enhanced seismic performance. The study produces design guidelines for engineers detailing the application of modern concrete technologies to improve the resilience and safety of bridge infrastructure in seismic regions, bridging the gap between traditional design practices and the latest innovations in material science.

The rest of the study is organized as follows: The next section presents a comprehensive literature review that examines existing work and identifies gaps in previous studies. The materials and methods section then details the materials used and the step-by-step process of the proposed experimental approach.

2. Literature Review

In this section, researchers discuss several studies related to Performance-Based Seismic Analysis of Bridge Piers: A Study in Concrete Technology.

Chen et al. (2023) [26] examined the seismic performance of piers that were laced with concrete-filled steel tubular (CFST). Next, finite element models were either simplified finite element models (S-FEM) or refined finite element models (R-FEM) using CFST-laced piers. By comparing several methods, it was determined that the S-FEM significantly enhanced the efficiency of analysis while also satisfying the accuracy standards of engineering analysis. Also, the S-FEM approach was used to study the seismic behavior of a bridge that included piers that were laced with CFST and connected by flanges. Structural considerations such as pier elevation axial compression ratios, CFST column steel proportions, steel lacing tube layout, and longitudinal slope were taken into account to improve the bridge's design scheme. The results indicated that axial pressure ratios of 0.1 and longitudinal slopes of 1:30 significantly enhanced seismic performance.

Wang et al. (2021) [27] assessed the seismic performance of Hollow Steel Tube (HST) and Prestressed Concrete-Filled Steel Tube (PCFST) piers for bridges with different superstructure eccentricities. Six seismic waves were created to accommodate uncommon earthquake ground classification changes. Analysis showed that the superstructure's eccentricity did not affect the HST bridge piers' and PCFST bridge piers' largest longitudinal (LG) displacement responses. When exposed to lateral ground vibrations, bridge piers displayed a larger transverse (TR) displacement reaction as eccentricity (e/H) increased from 0 to 0.2. This suggested that eccentricity affected the seismic behavior of the two pier types. During simulations, the PCFST pier showed high ductility and bearing capacity, increasing the bridge system's seismic performance.

Farzana et al. (2020) [28] investigated the tensile behavior of a stainless steel-reinforced bridge pier, paying particular attention to its hysteresis energy dissipation capability. This experiment employed a direct displacement-based design method. Ten separate earthquake data sets were used for a nonlinear time history analysis following an experimental investigation of the Stainless Steel (SS) rebar's tensile characteristics. The goal was to watch and evaluate how a bridge pier was strengthened with stainless steel compared to a more traditional bridge pier that was reinforced with carbon steel. Findings showed that the correlation between damping and flexibility has a coefficient of determination (R^2) higher than 96%.

Pang et al. (2020) [29] investigated the fragility functions that affected the seismic performance of bridge piers in reaction to far-field and near-fault ground motions, taking into consideration flexural and brittle failure processes at different damage stages. By establishing the link between the Engineering Demand Parameter (EDP) and Intensity Measure (IM), the fragility curves of piers were generated using Cloud Analysis and Incremental Dynamic Analysis (IDA). By evaluating EDPs that relied on deformation and those that relied on force, IDA confirmed that Cloud Analysis was reliable. By creating fragility curves, researchers looked at how different fiber kinds affected the seismic behavior of FRC bridge piers. According to the results, the seismic requirements for Fiber Reinforced Concrete (FRC) piers were raised by around 5%, while for Reinforced Concrete (RC) piers, the increase was 10%, in comparison to far-field earthquakes that were detected near the fault.

Wakjira et al. (2020) [30] examined the effects of significant design parameters on the functionality of rectangular reinforced concrete (RC) bridge piers consolidated with steel-reinforced polymer (SRP) compounds under seismic activity. Using a three-level fractional factorial design of experiments at 5% significance, concrete compression strength, steel bar yield strength, longitudinal bar geometric ratio, internal longitudinally reinforced spacing, pier aspect ratio, and retrofitting SRP layers were examined. The results show that the ductility and lateral load-carrying capabilities of SRP-confined RC bridge piers were affected by longitudinal and transverse reinforcement, pier aspect ratio, and material quality. Adding SRP layers increased ductility and base shear resistance.

Billah et al. (2018) [31] evaluated seismic risk for concrete bridge piers reinforced with Ni-Ti, Cu-Al-Mn, and Fe-based Shape Memory Alloy (SMA) rebars, considering various seismic hazard scenarios. Pier response was evaluated using probabilistic seismic demand models that were generated from incremental dynamic analysis. A comparison of five SMA-RC piers' performances was illustrated by fragility curves that were derived from maximum and residual drift. Annual exceedance rates for different damage levels were compared on seismic hazard curves. The findings showed that the SMA-

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RC piers had extremely low collapse probabilities, even in the greatest earthquakes. Among the study's piers, the FeNCATB-SMA reinforced pier (SMA-3) stood out for its exceptional performance.

De et al. (2017) [32] examined the seismic response using state-of-the-art and highly efficient dynamic non-linear analysis. Formulations that were both simplified and reliable, derived from codes or experiments, were employed to evaluate the seismic behavior of both ductile and brittle components. Numerical simulations partially verified these formulations. Two separate limit states, damage limitation and collapse, were taken into account when building fragility curves using cloud analysis and Incremental Dynamic Analysis (IDA). The updated numerical models showed that the delicate parts of the bridge system deformed more when strong ground motions came from nearby sources than when they came from far away sources. However, the likelihood of failure was higher when considering fragility curves in comparison to far-field records.

Billah et al. (2016) [33] developed damage states for SMA and Reinforced Concrete (RC) bridge piers based on performance in different seismic situations. For various SMAs, IDA was used to construct quantified damage states for yielding, cracking, and strength deterioration, with particular probability distributions. An additional set of damage states based on residual drift was provided. A functional relationship between maximum drift, super elastic strain of SMA, and residual drift was defined analytically. The results demonstrated that the equation accurately predicted residual drift when compared to experimental data.

3. Materials and Methods

This section details the materials used, including high-strength concrete, steel reinforcement, and SMA, and describes the experimental processes used to assess the seismic conductivity of bridge piers by means of a variety of testing procedures and analytics tools.

3.1. Materials

The study employed high-strength concrete, steel reinforcement, and SMA to assess the seismic performance of bridge piers. The main focus was on the mechanical qualities of the piers to improve their longevity and ability to withstand seismic occurrences.

- **Concrete**

Concrete is a fundamental material in the construction of reinforced concrete (RC) structures due to its high compressive strength, durability, and versatility. The seismic performance of concrete is crucial as it directly affects the resilience and stability of structures during and after seismic events. Advances in concrete technology have led to the development of high-strength concrete, which is particularly beneficial in bridge pier construction. Figure 2. depicts the concrete setup procedure.

Figure 2. Concrete [34]

The primary role of concrete in seismic applications is to provide a strong and stable foundation that can withstand significant compressive forces while maintaining its structural integrity [35]. Bridge pier performance-based seismic analysis evaluates how piers respond to earthquakes, setting specific performance goals. Table 1 shows bridge pier seismic analysis material properties: a compressive strength of 38.7 MPa with a strain of 0.00205, indicating load-bearing and deformation capacity; a tensile strength of 3.45 MPa, indicating tensile resistance; and an elastic modulus of 29.707 GPa, indicating material stiffness necessary to predict seismic performance.

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Table 1. Mechanical Properties of Concrete

Property	**Value**
Compressive Strength	38.7 MPa
Corresponding Strain	0.00205
Tensile Strength	3.45MPa
Elastic Modulus	29.707GPa

These properties are typical for high-strength concrete used in bridge pier construction.

- **Steel Reinforcement**

Steel reinforcement, also known as rebar, is widely used in RC structures to enhance their tensile strength and ductility. The primary advantage of using steel reinforcement is its ability to absorb and dissipate energy during seismic events, thereby reducing the likelihood of sudden structural failure. Steel's high tensile strength, combined with its ductility, makes it an essential component in the construction of seismic-resistant structures. The reinforcement bars are typically embedded within the concrete to create a composite material that can withstand both compressive and tensile forces, thus boosting structure seismic performance [36]. Steel reinforcement, also known as rebar, is widely used in RC structures to enhance their tensile strength and ductility. Figure 3 illustrates a detail of a steel pier designed to resist seismic events. The steel pier body is anchored to a base plate, which is then connected to a reinforced concrete (RC) foundation using foundation bolts.

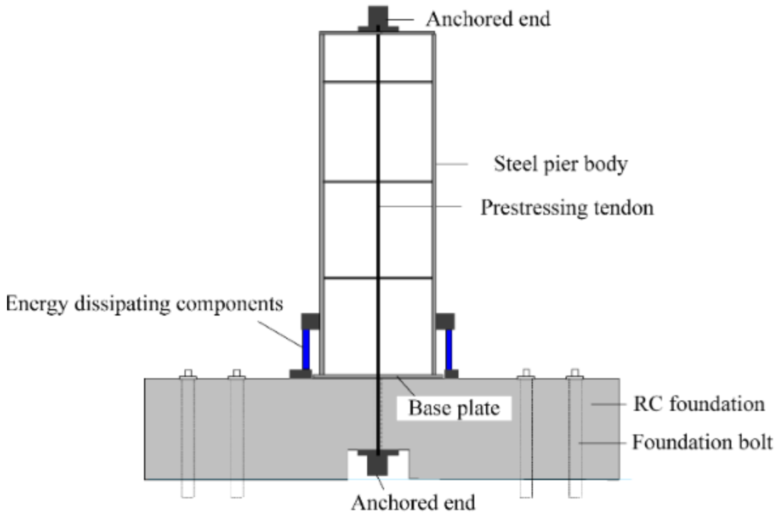

Figure 3. Steel Bridge pier structure [37]

Table 2 outlines material properties crucial for seismic analysis of bridge piers: yield stress of 525 MPa indicating the stress point of permanent deformation, strain hardening parameter of 0.5 showing the rate of strength increase post-yield, and elastic modulus of 200 GPa signifying the material's stiffness.

Table 2. Mechanical Properties of Steel Reinforcement

Property	**Value**
Yield Stress	525 MPa
Strain Hardening Parameter	0.5
Elastic Modulus	200 GPa

This type of steel provides the necessary ductility and strength to withstand seismic forces.

- **Shape Memory Alloy (SMA)**

SMA is a unique material that can deform significantly and rebound to its original shape after stress removal. This super elasticity makes SMA a good contender for increasing RC structure seismic performance. SMA can absorb and diffuse seismic energy in beams and columns' plastic hinge zones, decreasing residual deformations and improving the structure's ability to recover. In seismic design, SMA improves structure ductility and energy dissipation, boosting resilience and post-earthquake functionality [38].

Figure 4 displays two perspectives of seismically engineered concrete structures reinforced with SMA strips and bars made of iron.

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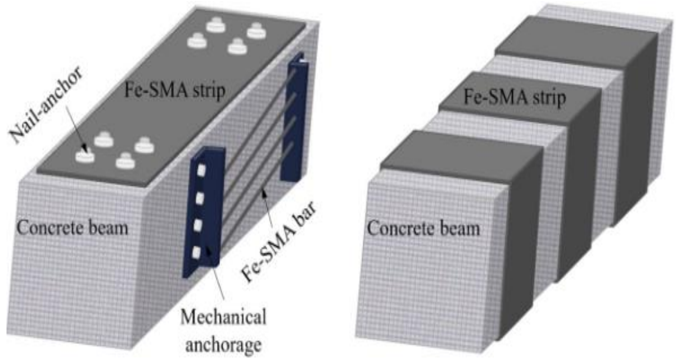

Figure 4. Illustration of Concrete Beams Reinforced with SMA Strips and Bars [39]

Table 3 presents material properties for seismic analysis: austenite-to-martensite starting stress (320 MPa) and finishing stress (442.5 MPa), martensite-to-austenite starting stress (210.8 MPa) and finishing stress (122 MPa), super elastic plateau strain length (6.13%), and modulus of elasticity (98.4 GPa), crucial for performance prediction.

Table 3. Mechanical Properties of Shape Memory

Property	**Value**
Austenite-to-Martensite Starting Stress	320 MPa
Austenite-to-Martensite Finishing Stress	442.5 MPa
Martensite-to-Austenite Starting Stress	210.8 MPa
Martensite-to-Austenite Finishing Stress	122 MPa
Superelastic Plateau Strain Length	6.13 %
Modulus of Elasticity	98.4 GPa

The inclusion of SMA is aimed at enhancing seismic performance due to its superelastic properties and ability to dissipate energy [40].

3.2. Methods

The study involved preparing bridge pier specimens, subjecting them to quasi-static cyclic and dynamic shake table tests, and analyzing the data to evaluate seismic performance using hysteresis curves, stress-strain relationships, and finite element modeling.

- **Specimen Preparation**

Bridge pier specimens were designed and constructed using the specified materials. The concrete was mixed and poured into moulds to form the pier columns. Steel reinforcement bars were embedded within the concrete to provide tensile strength. In some configurations, SMA bars were also incorporated to study their effect on seismic performance.

- **Seismic Testing**

Bridge piers were tested under quasi-static cyclic loading and dynamic shake table tests to simulate seismic forces and evaluate their performance.

❖ **Quasi-Static Cyclic Loading Tests:** The bridge piers underwent quasi-static cyclic loading to replicate the stresses **experienced** during an earthquake. The loading pattern followed a predefined protocol, gradually increasing in amplitude until the specimen reached failure. The primary aim was to observe the hysteretic behavior and energy dissipation capacity of the piers [41]. The energy dissipation at the i-th cycle, Δ_i, is given by:

$$\Delta_{\mathrm{i}} = \Delta_0 + \mathrm{i}.\Delta_{\mathrm{inc}} \quad (1)$$

where Δ_i is the energy dissipation at the i-th cycle, Δ_0 is the initial energy dissipation, and Δ_{inc} is the incremental increase in energy dissipation per cycle.

❖ **Dynamic Shake Table Tests:** Selected specimens were mounted on a shake table to apply dynamic loads replicating real earthquake ground motions. This testing method helped to evaluate the dynamic response of the piers, including natural frequency, damping ratio, and overall stability under seismic conditions [42]. The equation governing the dynamic response is given by:

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$$Mu(t) + Cu(t) + Ku(t) = F(t) \quad (2)$$

where:
M is the mass matrix,
C is the damping matrix,
K is the stiffness matrix,
u(t) is the displacement vector,
F(t) is the external force vector, typically representing the seismic excitation.

- **Instrumentation**

Instrumentation included strain gauges, displacement transducers, and load cells to measure strain distribution, lateral displacements, and applied loads during testing.

- **Strain Gauges:** Strain gauges were attached to the steel and SMA reinforcements as well as to the concrete surface to measure strain distribution during loading.
- **Displacement Transducers:** Linear variable differential transformers (LVDTs) were used to record lateral displacements and deformations of the piers.
- **Load Cells:** Load cells were installed to monitor the applied loads accurately during both quasi-static and dynamic tests.

- **Data Analysis**

Data analysis involved plotting hysteresis curves, generating stress-strain relationships, and ascertaining the causes of failure to evaluate the piers' seismic performance.

- **Hysteresis Curves:** The load-displacement data acquired from the cyclic tests were utilized to construct hysteresis curves, offering valuable information on the energy absorption and ductility of the piers [43]. The energy dissipated in each cycle, E_d, is calculated by:

$$E_d = \oint \sigma d\varepsilon \quad (3)$$

where E_d is the energy dissipated in each cycle, σ is the stress, and ε is the strain.

- **Stress-Strain Relationships:** The recorded strain data were used to generate stress-strain relationships for concrete, steel, and SMA, which helped in understanding the material behavior under seismic loading [44]. The stress, σ, is given by:

$$\sigma = E . \varepsilon + k(\varepsilon - \varepsilon_y)^n \quad (4)$$

where σ is the stress, E is Young's modulus, ε is the strain, ε_y is the yield strain, and k and n are material-specific constants.

- **Failure Modes:** Observations and measurements from the tests were analyzed to determine the failure modes of the piers, including cracking patterns, spalling of concrete, and yielding of reinforcement.

- **Finite Element Modeling**

Finite element models of the bridge piers were developed using software such as ABAQUS or ANSYS simulators. The models integrated the material attributes and geometry of the specimens. The piers' seismic behavior was predicted, and the experimental results were evaluated using numerical simulations [45].

4. Results and Discussion

This section demonstrates the main findings of the research that are obtained after the implementation of the proposed materials and methods.

- **Results based on Quasi-Static Cyclic Loading test**

Table 4 presents data from a Quasi-Static Cyclic Loading Test conducted on three different materials: concrete, steel reinforcement, and Shape Memory Alloy (SMA). The test measures the displacement (in mm) and corresponding force (in kN) for each material across five loading cycles. For concrete, the displacement increases from 0.5 mm to 2.5 mm, with corresponding forces escalating from 50 kN to 180 kN. Similarly, steel reinforcement shows displacement ranging from 0.6 mm to 2.7 mm, with forces increasing from 60 kN to 200 kN. For SMA, displacement varies from 0.4 mm to 2.0 mm, and forces rise from 40 kN to 170 kN. The data illustrates the progressive load-bearing capacity and deformation characteristics of each material under cyclic loading conditions.

Table 4. Results of Quasi-Static Cyclic Loading tests

Cycle	Concrete		Steel		SMA	
	Displacement (mm)	Force (kN)	Reinforcement Displacement (mm)	Reinforcement Force (kN)	Displacement (mm)	Force (kN)
1	0.5	50	0.6	60	0.4	40
2	1.0	100	1.2	110	0.8	90
3	1.5	140	1.8	150	1.2	130
4	2.0	170	2.3	180	1.6	160
5	2.5	180	2.7	200	2.0	170

- **Results based on the Dynamic Shake table test**

Table 5 presents results from a dynamic shake table test, evaluating the performance of concrete, steel reinforcement, and Shape Memory Alloy (SMA) under varying frequencies (Hz). The test measures displacement (mm) and acceleration (m/s^2) at frequencies ranging from 1 Hz to 5 Hz. For concrete, displacement increases from 0.4 mm to 2.1 mm with corresponding acceleration from 0.5 m/s^2 to 2.2 m/s^2. Steel reinforcement shows displacement rising from 0.5 mm to 2.3 mm and acceleration from 0.6 m/s^2 to 2.5 m/s^2. SMA displays displacement from 0.3 mm to 1.8 mm, with acceleration increasing from 0.4 m/s^2 to 2.0 m/s^2. The data showcases the displacement and acceleration response of each material when subjected to dynamic loading conditions, offering valuable insights into their behaviour and resilience in the context of seismic events.

Table 5. Results of Dynamic Shake Table tests

Frequency (Hz)	Concrete		Steel		SMA	
	Displacement (mm)	Acceleration (m/s^2)	Reinforcement Displacement (mm)	Reinforcement Acceleration (m/s^2)	Displacement (mm)	Acceleration (m/s^2)
1	0.4	0.5	0.5	0.6	0.3	0.4
2	0.9	1.0	1.1	1.2	0.7	0.9
3	1.3	1.4	1.5	1.6	1.1	1.3
4	1.6	1.7	1.9	2.0	1.4	1.6
5	2.1	2.2	2.3	2.5	1.8	2.0

- **Stress-Strain relationships**

Table 6 presents the stress-strain relationship for concrete, steel, and Shape Memory Alloy (SMA). At a strain of 0.001, the stress for concrete is 20.0 MPa, for steel is 200 MPa, and for SMA is 150 MPa. As the strain increases to 0.002, the stress values increase to 30.0 MPa for concrete, 400 MPa for steel, and 250 MPa for SMA. At 0.003 strain, the stresses are 35.0 MPa for concrete, 500 MPa for steel, and 300 MPa for SMA. For a strain of 0.004, the stress increases to 37.0 MPa for concrete, 520 MPa for steel, and 320 MPa for SMA. Finally, at 0.005 strain, the stress values reach 38.7 MPa for concrete, 525 MPa for steel, and 442.5 MPa for SMA.

Table 6. Stress-Strain Relationship for Concrete, Steel, and Shape Memory Alloy (SMA)

Strain	Concrete Stress (MPa)	Steel Stress (MPa)	SMA Stress (MPa)
0.001	20.0	200	150
0.002	30.0	400	250
0.003	35.0	500	300
0.004	37.0	520	320
0.005	38.7	525	442.5

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Figure 5 shows stress responses for concrete, steel, and SMA at varying strain levels, highlighting their mechanical behaviors.

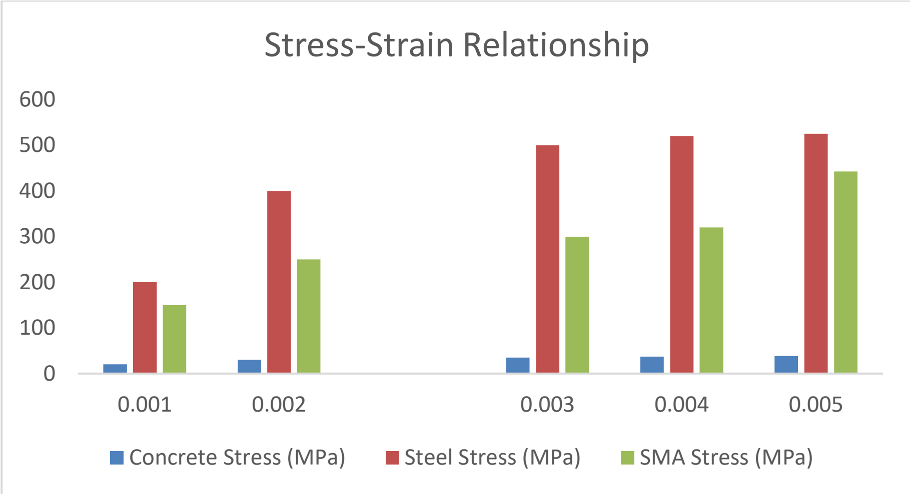

Figure 5. Stress-Strain Behavior of Concrete, Steel, and Shape Memory Alloy (SMA)

- **Hysteresis Curve**

Figure 6 illustrates the hysteresis curves for concrete, steel, and Shape Memory Alloy (SMA), depicting the force (kN) versus displacement (mm) relationship. As displacement increases from 0.5 mm to 2.5 mm, the force experienced by each material also increases. Concrete shows a gradual increase in forcse from 60 kN to 180 kN. Steel exhibits a more significant rise from 60 kN to 200 kN, while SMA increases from 40 kN to 170 kN. The curves highlight the energy dissipation and material response under cyclic loading conditions.

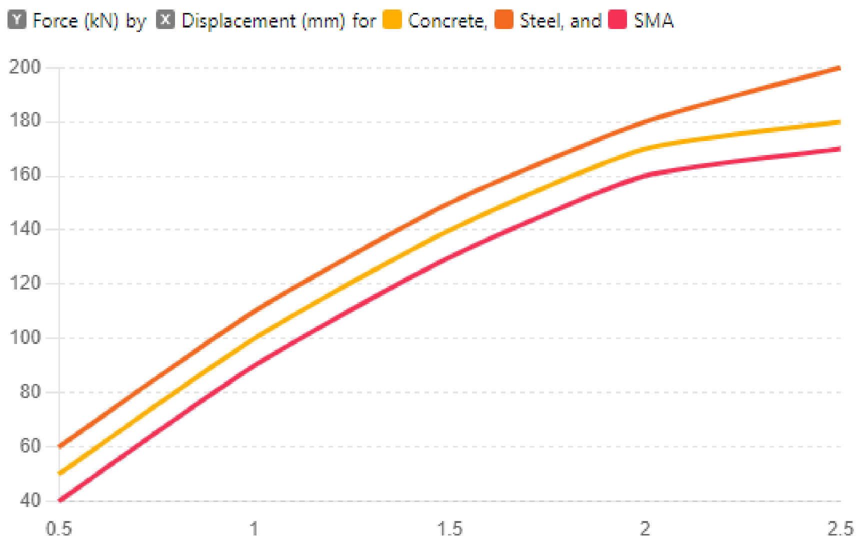

Figure 6. Hysteresis Curves of Concrete, Steel, and Shape Memory Alloy (SMA)

5. Conclusion and Future Scope

Performance-based seismic analysis is a method of evaluating the behavior of structures, such as bridge piers, under seismic forces to ensure their safety and functionality during and after earthquakes. This study focuses on the mechanical properties and seismic performance of bridge piers constructed with high-strength concrete, steel reinforcement, and Shape Memory Alloy (SMA). The primary objectives are to enhance the longevity and seismic resilience of bridge piers. Quasi-static cyclic loading and dynamic shake table tests are among the models used. The proposed model integrates SMA with traditional materials, aiming to improve energy dissipation and minimize residual deformations. The steps of the model involve specimen preparation, seismic testing, instrumentation, data analysis, and finite element modeling. Results show that SMA-reinforced piers exhibit improved performance, with SMA stress reaching 442.5 MPa at a 0.005 strain and steel yield stress reaching 525 MPa. The future scope includes further optimization of material compositions and testing under varied seismic conditions. The proposed model demonstrates significant enhancements in seismic performance, providing a robust framework for performance-based seismic analysis of bridge piers. This study underscores the critical role of advanced materials in achieving resilient infrastructure, highlighting the potential for SMA in modern seismic design.

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