



REVIEW

Research Review on the Seismic and Vulnerability Performance of Prefabricated Assembly Double Column Piers

Yu-Xuan Ding¹, Xiao-Hui Yu¹, Cheng-Quan Wang^{2,*}, Rui-Rui Qian², Zi-Hao Ren², Zhi-Hao Zhai¹
and Jing-Yao Liu³

¹College of Civil Engineering and Architecture, Guilin University of Technology, Guilin, China

²School of Engineering, Hangzhou City University, Hangzhou, China

³School of Civil Engineering and Architecture, East China Jiao tong University, Nanchang, China

*Corresponding Author: Cheng-Quan Wang. Email: wangcq@hzcw.edu.cn

Received: 31 March 2026; Accepted: 13 May 2026; Published: 23 October 2026

ABSTRACT: This paper presents a comprehensive review of seismic vulnerability assessment for prefabricated assembly double-column pier bridges. The primary objective is to critically examine the key vulnerability parameters and their coupling mechanisms while outlining future pathways for enhancing seismic resilience. The review identifies essential vulnerability indicators, including displacement, acceleration, and composite damage indices. It further contrasts dominant research trends, noting that domestic investigations concentrate largely on geometric configurations and pier-to-pier interactions, whereas international studies prioritize multifactor coupling effects. A central focus of the review is the analysis of complex parameter interactions, specifically how pier geometry, material nonlinearity, and joint connection details collectively shape structural fragility under varied seismic inputs. Finally, the paper integrates the concept of recoverable functionality into the vulnerability assessment framework. The principal conclusions underscore the necessity of standardized coupling analysis and advocate for the quantitative incorporation of emerging smart materials such as shape memory alloys and self healing concrete to directly refine probabilistic fragility curves and improve post earthquake recovery outcomes. This review offers a theoretical foundation for advancing performance-based seismic design and resilience evaluation of modern bridge systems.

KEYWORDS: Prefabricated assembly-type double-column pier bridges; vulnerability analysis; comparison of vulnerability parameters; application of new materials; post-disaster recovery

1 Introduction

The double-column pier bridge, as an important type of bridge structure, is widely used under large spans and complex terrain conditions. Compared to traditional single-column pier bridges, double-column pier bridges exhibit stronger stability and seismic resistance due to their unique structural characteristics [1,2]. However, under strong seismic actions, the seismic performance of double-column pier bridges may still be affected by various factors, especially under long-term use and aging conditions, where the vulnerability of the structure becomes a significant issue [3,4]. Vulnerability analysis, as an important component of bridge seismic research, aims to assess the safety and durability of bridges under different seismic intensities by quantifying the probability of structural damage.

How to comprehensively understand the influence mechanisms of various parameters and make comparisons and selections based on actual needs remains a significant challenge in current research.

This review aims to summarize the main achievements of recent studies on the vulnerability of double-column pier bridges both domestically and internationally, focusing on analyzing and comparing the roles and impacts of different vulnerability parameters in the seismic performance assessment of bridges, and exploring the applicability and limitations of each parameter under different seismic conditions. This review therefore aims to systematically synthesize recent advances in vulnerability assessment for double column pier bridges with a specific and sustained focus on three interconnected themes: the complex coupling effects among geometric parameters material properties and seismic input characteristics the integration of restorable function design principles into performance evaluation and the fundamental role of inter column connection and joint details in accurately capturing seismic numerical response and vulnerability outcomes [5].

2 Project Background

2.1 Basic Seismic Characteristics of Double-Column Pier Bridges

Double-column pier bridges are supported by two piers that bear the bridge deck, jointly bearing external loads through the connection between the piers and the deck. In an earthquake, the seismic performance of double-column pier bridges may be more complex compared to single-column pier bridges, as factors such as the interaction between the double columns, the spacing between the piers, and material properties all influence the dynamic response of the bridge. Double-column pier bridges are widely used in large-span, high-strength bridge engineering, especially in seismically active areas. The double-column pier structure is typically suitable for larger bridge spans, effectively distributing loads and avoiding excessive eccentric torsion issues that may occur with single-column piers [6,7].

The seismic performance analysis of a two-column pier bridge focuses on the dynamic response of the bridge under seismic action, especially the effect of the interaction between the piers and columns on the overall structure [8,9]. The vibration induced by seismic waves leads to the bending, shear and torsional responses of the bridge as shown in Fig. 1. Twin-column pier structures may experience more complex torsional effects and asymmetric deformations due to their relatively large pier spacing [10]. The analysis of seismic performance usually adopts the methods of finite element analysis, time-course analysis and modal analysis to assess the damage modes and damage probability under different seismic intensities by simulating the response of bridges under the action of different types of seismic waves (e.g., near-field vs. far-field earthquakes). Factors such as the intrinsic frequency, stiffness, damping characteristics of the structure and the geometry and material properties of the piers and columns all have an important impact on the seismic capacity of the bridge, which in turn affects the results of its vulnerability assessment [11,12].

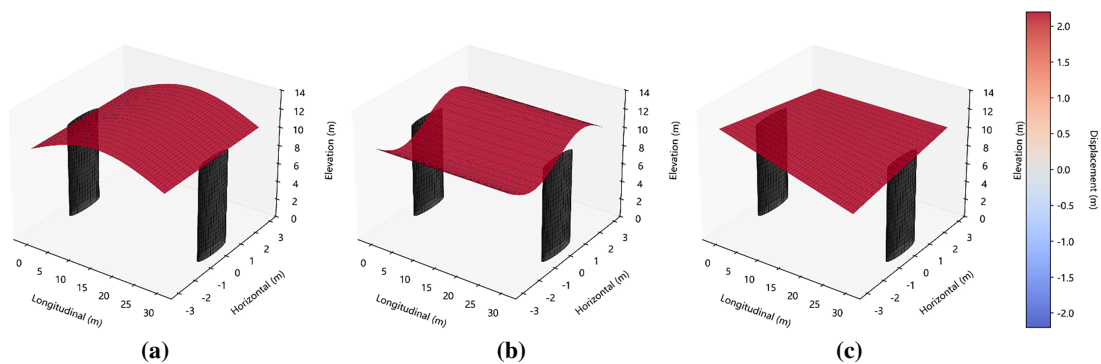


Figure 1: Dynamic response state of double-column pier bridges, (a) Curved state, (b) Shear state, (c) Twisted state.

2.2 Basic Characteristics of Damage in Double-Column Pier Bridges

The damage characteristics of double-column pier bridges are particularly significant under seismic action, mainly in the deformation of the structure, crack extension, component failure and other aspects. Compared with the single-column pier bridge, double-column pier structure due to the relative action between the pier and the complexity of the bridge components, its damage mode is more complex and diverse. As early as in the 1976 Tangshan earthquake, bridge double-column pier has been more applications, and many double-column pier bridges have been damaged, such as the female weaving Zhai Bridge in Tangshan City, Yuehe Bridge, power plant seven bridge and Luan xian Lei Zhuang Shahe Highway Bridge as well as located in the Ji Canal Highway Bridge in the Han gu District of Tianjin City, such as double-column simply supported girder bridges, the occurrence of the pier concrete cracking, rebar exposure, the pier body tilted and shear damage and complete collapse and other varying degrees of earthquake damage. collapse, and other different degrees of earthquake damage [13]. In the 1999 Taiwan Gathering earthquake, according to the investigation report released by the Ministry of Transportation and Communications of Taiwan, a total of more than 1000 bridges were affected by the earthquake, of which about 40 bridges were so severely damaged that they could not continue to be used. The damage of root cracks and damage of double-column pier bridges is more prominent, accounting for about 20%–30% of the total damaged bridges, and the deck slabs of some bridges are fractured or misaligned, especially in the older bridges, and the bearing damage is especially prominent. About 1500 bridges were severely damaged in the Wenchuan Earthquake in China in 2008, and in most of the damaged bridges, the cracks of the pier columns and the bearings of the double-column pier bridges are damage were more serious, and the damage of double-column pier bridges in the earthquake was more prominent. Wenchuan earthquake disaster area, double-column pier structure is mainly used in simply supported and continuous girder bridges, arch bridges, cable-stayed bridges and suspension bridges in the application of very little, the statistics of 783 bridges with piers pier form mainly single-column piers, double-column piers, hollow thin-wall piers and gravity solid piers, a total of 3411 piers, of which the double-column piers are 2823, accounting for 83% [14]. The Great East Japan Earthquake of 2011 according to the data released by the Ministry of Transportation of Japan, the post-earthquake survey showed that about 1500 bridges had suffered different degrees of damage, and about 20 bridges had completely lost their functions. For example, in Fukushima and Sendai, about 10%–20% of the bridges were damaged in the deck slabs and superstructures, and the abutment foundations were cracked or plastically deformed severely [15,16]. 2016 Central Italy Earthquake, according to the survey data from the Italian Ministry of Transportation, about 500 bridges were damaged due to damage to the bearings and joints in the 2016 earthquake, and about 10%–15% of the bridges were damaged due to bearing and abutment damage is so severe that they can no longer be used [17]. The statistical information pertaining to bridge and pier damage presented in this review was compiled from published post earthquake field investigation reports including those following the Wenchuan earthquake and other major seismic events [2–5]. According to the survey data documented in these sources a total of 2334 bridges situated on national and provincial trunk highways within seismic intensity zones ranging from VI to XI were examined. Among this inventory 1325 bridges were identified as employing double column pier configurations while 574 bridges utilized single column piers and 435 bridges were of alternative structural types as illustrated in Fig. 2. With respect to double column piers a total of 4673 individual columns were assessed. The documented damage manifestations included foundation cracking plastic deformation and column tilting which collectively accounted for 1402 cases. Damage associated with bridge deck slabs and superstructures totaled 1635 cases with deck misalignment and fracture being particularly prevalent. Furthermore damage to bearings and connecting components involving bearing failure and displacement was observed in 1168 instances. Non structural damage was recorded in 468 cases as shown in Fig. 3. These aggregated observations based on the surveyed literature

suggest that double column piers were extensively utilized in small to medium span simply supported girder bridges and continuous girder bridges within the affected regions and that superstructure related damage constituted a significant proportion of the documented pier damage.

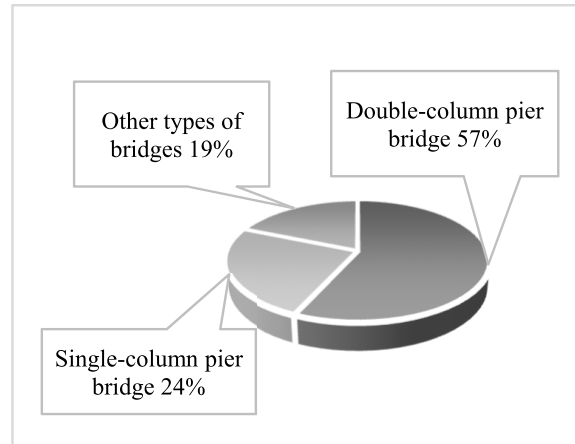


Figure 2: Statistics of bridge numbers by pier type.

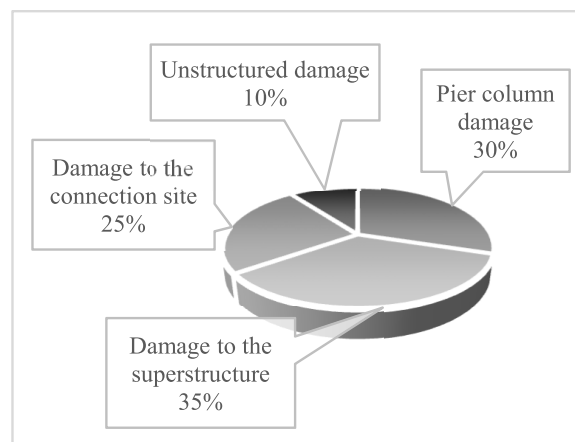


Figure 3: Statistics of damage types for double-column piers.

2.3 Overview of Double Column Pier Vulnerability Analysis

Current research on the seismic performance and vulnerability of precast assembled double-column piers has evolved from validation of single connection types to systematic investigations into how multiple prefabricated components—such as grouted splice sleeves, hybrid connections, socket connections, dry joints, and rocking interfaces—alter structural damage patterns and vulnerability. Studies indicate that different prefabricated connection methods exhibit distinct characteristics in terms of load-bearing capacity, energy dissipation, self-centering ability, and residual displacement. Grouted splice sleeve connections can effectively replicate the energy dissipation performance of cast-in-place piers, yet their failure locations and damage evolution paths differ fundamentally from those of conventional cast-in-place structures. Hybrid connection designs seek a balance between energy dissipation and self-centering capacity. Socket connections, by utilizing Ultra-High Performance Concrete grouting, achieve an ideal mechanism where damage is concentrated in the pier shaft while the connection zone remains elastic. Regarding damage assessment,

fragility analysis has expanded from traditional displacement-based single-parameter approaches to refined evaluations that incorporate multi-dimensional indicators such as prestress loss, strength degradation, and self-centering capacity. As shown in Table 1, fragility studies on dry-joint piers with shape memory alloy bars demonstrate that modifications in construction details can effectively reduce the exceedance probability of structures under different seismic intensity levels, providing a theoretical basis for the application of precast assembled bridge piers in high-intensity seismic regions.

Table 1: Effects of prefabricated component types on damage and vulnerability of double-column piers.

Prefabricated Component Type	Influence on Damage Mode	Influence on Vulnerability
Grouted Splice Sleeve Connection	Damage mode similar to cast-in-place piers (crushing at base or bar fracture); connection zone may fail in shear for short columns.	High energy dissipation, plump hysteresis, high equivalent stiffness; higher residual capacity after impact than cast-in-place; connector location matters.
Hybrid Connection	Damage concentrated at pier base or splicing interface, small residual displacement; CFST segmental piers show no obvious damage under large drift.	Balances energy dissipation and self-centering; CFST columns have slow strength degradation and excellent deformability, reducing collapse vulnerability.
Socket Connection	Damage concentrated at pier base, socket interface elastic, no damage in connection zone.	Small residual displacement; UHPC grouting enhances bond; controllable damage facilitates rapid repair.
Dry Joint/Rocking Interface	Controllable opening/closing at rocking joints, low damage in pier shaft; multiple interfaces cause higher prestress loss.	Strong self-centering but low energy dissipation; SMA bars reduce displacement response; shear links dissipate energy preferentially, lowering overall vulnerability.

Common vulnerability parameters of double-column pier bridges include displacement, acceleration, damage index, plastic deformation, shear, strain and crack width. Xie and Sun analyzed the seismic performance of double-column pier bridges, combined numerical simulation and seismic measured data, and proposed a method to assess the susceptibility under different seismic measures, emphasizing the important influence of bearing type, pier design, etc., on the susceptibility of bridges [18]. In addition, displacement and acceleration are commonly used to assess the dynamic response and the degree of seismic damage of the structure, and displacement exceeding the standard usually implies serious damage or failure. Lu et al. analyzed the damage state of double-column pier bridges under different seismic intensities, and proposed a comprehensive assessment method based on displacement, acceleration, and damage indices, which showed that the vulnerability of double-column pier bridges during large earthquakes is mainly manifested by plastic deformation of piers and columns, as well as the damage of the bearings [19]. Pang et al. reviewed the recent research progress on seismic vulnerability analysis of double-column pier bridges

in recent years [20], in which the damage index integrates multiple response indicators, such as displacement and plastic deformation, to quantify the overall damage level of the bridge. Plastic deformation and shear mainly reflect the nonlinear behavior and bearing capacity changes of piers and bearings, while strain and crack width are used to measure the degree of local damage or deformation of materials. These parameters are widely used in bridge susceptibility analysis to help researchers assess the damage probability and seismic performance of bridges under different seismic conditions.

3 Vulnerability Assessment Methods and Models

3.1 Traditional Vulnerability Analysis Methods

Vulnerability assessment based on mechanical models, time history analysis, and response spectrum method. The assessment methods based on mechanical models and response spectrum method are relatively simplified and suitable for the preliminary design stage, but they cannot accurately reflect the nonlinear response of structures. Time history analysis can more comprehensively simulate the behavior of bridges under actual seismic actions, capturing the nonlinear response of bridge piers and providing more accurate vulnerability assessment results [21]. Among them, Dong et al. analyzed the seismic vulnerability of bridges using the response spectrum method, noting that for double-column pier bridges, the dynamic characteristics of the piers and the span length of the bridge have a significant impact on their seismic performance. However, when considering the nonlinear behavior of the piers, the accuracy of the assessment may be affected [22]. Zhou et al. conducted a seismic vulnerability assessment of double-column pier bridges based on time history analysis, combining dynamic analysis to study bridge damage under different seismic inputs, demonstrating that the time history analysis method can accurately simulate the dynamic response of bridges during earthquakes, providing more reliable vulnerability assessment results than traditional response spectrum methods [23].

3.2 Modern Vulnerability Assessment Methods

Probabilistic methods, numerical simulation, finite element analysis, and dynamic analysis are the core methods of modern vulnerability assessment. They overcome the simplified assumptions and computational limitations of traditional methods, providing more accurate and reliable assessment results. Seify Asghshahr et al. combined Monte Carlo simulation with finite element analysis, considering the impact of the height of the column and the span of the bridge on vulnerability [24]. Sandıkkaya et al. conducted a vulnerability assessment of bridge piers based on probabilistic models, demonstrating that the failure probability of bridge piers is closely related to the characteristics of seismic waves (such as frequency content, duration, etc.) through the use of reliability analysis and seismic response simulation, indicating that strong motions, especially seismic waves with high-frequency components, have a greater damaging effect on bridge piers [25]. Li et al. simulated the response of bridges under nonlinear seismic actions through finite element analysis (FEA), showing that nonlinear finite element analysis can more accurately predict the damage to bridges during strong earthquakes, particularly for double-column piers, where nonlinear effects lead to more complex failure modes under strong earthquakes, including plastic deformation of the columns and sliding of the supports [26]. Dehghanpoor et al. analyzed the seismic performance of double-column piers under nonlinear seismic conditions through finite element simulation, exploring the failure modes of the piers, the formation of plastic hinges, and the damage development process, indicating that finite element analysis can effectively capture the complex response of piers under strong seismic actions [27]. Jiang and Sorensen combined numerical simulation with probabilistic analysis for the seismic vulnerability assessment of double-column piers, optimizing the design of double-column piers through parametric studies, showing that increasing the stiffness of the piers and using seismic isolation bearings can effectively

reduce seismic damage to bridges [28]. The effects of different types of seismic motions on precast segmental pier bridges were investigated using time history analysis. The results indicate that the duration and spectral characteristics of seismic motions significantly affect the damage state of the piers, while accurately capturing the interaction between segments and the nonlinear response at the joints. Probabilistic methods can effectively consider the uncertainties of bridges during earthquakes, finite element analysis can accurately simulate the nonlinear behavior of bridges, and time history analysis helps reveal the response and damage process of bridges under actual seismic motions. The combination of these methods can provide more precise bases for the seismic design, reinforcement, and safety assessment of double-column piers [29].

3.3 Experimental Research and Validation

Experimental research can verify the effectiveness of different vulnerability models and analysis methods, providing data support for optimization design, especially for nonlinear behavior (as shown in Table 2), energy dissipation and damage control studies (as shown in Table 3). Yang et al. used finite element analysis and bridge model tests, employing data collection methods such as accelerometers and displacement sensors, indicating that the inter-column interaction of double-column pier bridges has a significant impact on seismic performance, and that nonlinear responses are quite evident. The study suggests using high-precision model tests to capture the damage patterns of bridge piers under different seismic motions [30]. Qin et al. assessed the seismic performance of double-column pier bridges by combining shaking table experiments, time history analysis, and finite element simulations, using a three-dimensional shaking table to simulate seismic motions. Data was collected through dynamic accelerometers and displacement sensors, demonstrating that the damage to double-column pier bridges is closely related to inter-column interaction, pier material degradation, and seismic motion characteristics [31]. Yao et al. combined probabilistic methods and shaking table experiments, obtaining dynamic response data of the bridge on the shaking table through multi-point accelerometers and high-precision displacement sensors, proving that the characteristics of seismic waves (such as frequency, amplitude, etc.) have a significant impact on the degree of damage to bridges, and that the damage risk of double-column pier bridges under strong seismic actions is higher than that of single-column piers [32]. Kong et al. analyzed the vulnerability assessment of multi-column pier bridges under different seismic excitations, validating a vulnerability assessment model based on probabilistic analysis, indicating that the size, material properties of the pier columns, and seismic motion characteristics have a huge impact on damage patterns and vulnerability [33]. Possible future experimental directions, such as dynamic tests under high seismic amplitudes and studies on damage accumulation under long-term seismic actions, will further develop.

Table 2: Nonlinear mechanical behavior and numerical simulation.

Author	Year	Research Topic	Research Methods	Findings/Conclusion
Luo et al. [34]	2024	Explosion testing and dynamic response analysis	Experiments and numerical simulations	Damage assessment of concrete components under contact explosion
Dong et al. [35]	2022	The impact of horizontal beams on the seismic performance of double-column piers	Establishing numerical models for seismic resistance of non-beam and ductile beam systems	It can enhance the seismic resistance of double-column piers and has a good energy dissipation effect

(Continued)

Table 2 (continued)

Author	Year	Research Topic	Research Methods	Findings/Conclusion
Si et al. [36]	2022	Analysis and verification of seismic performance of connecting girder double-column bridge piers	Using pseudo-static tests to numerically simulate concentrated plastic hinges and fiber elements	The two results are consistent, which is a reliable method for the seismic resistance of shear link beams with double-column piers

Table 3: Research on energy dissipation and damage in vibration reduction.

Author	Year	Research Topic	Research Methods	Findings/Conclusion
Qin et al. [37]	2024	Development of a new type of self-centering variable friction dissipative support (SCVFB)	Establishing a model to study the mechanical properties of SMA plates	SCVFB's energy dissipation capacity and self-centering reduces residual bridge displacement
Nguyen et al. [38]	2025	Vulnerability of SCEB Double-Pier Bridge Piers under Near-Field Pulse-Type Seismic Lateral Excitation	Seismic vulnerability analysis using incremental dynamic analysis method	The additional self-resetting capability of SCEB can reduce the failure probability of bridge pier structures
Zhou et al. [39]	2024	The effect of using BRB for seismic retrofitting of double-column bridge piers	Nonlinear time history response analysis method	BRB can reduce the inelastic demand of columns and improve structural performance

4 Comparison of Vulnerability Parameters

4.1 Comparison of Domestic and International Research Status

In the surveyed domestic literature research attention has tended to emphasize the characteristics of conventional bridge systems with considerable focus directed toward the geometric configuration of bridge piers the interaction between adjacent columns and the influence of material properties on vulnerability outcomes [40]. Commonly adopted analytical approaches include finite element modeling damage index evaluation and time history analysis with an emphasis on characterizing the dynamic response and damage progression of bridge structures subjected to seismic wave excitation. Within the domestic context there appears to be a notable concentration on pier column dimensions and column to column interaction as geometric factors affecting vulnerability and a comparatively more detailed examination of pier geometry has been undertaken. Experimental investigations frequently integrate shaking table testing with finite element simulations for mutual validation and damage quantification is often pursued through the application of damage index methodologies. That said the methodological repertoire remains relatively conventional with finite element based and time history based investigations being particularly widespread. It may also be

observed that comprehensive consideration of multiple seismic input scenarios is not always fully realized and certain studies appear to offer limited validation with respect to complex seismic wave characteristics and long period ground motion effects [41–43].

Foreign scholars' research focuses more on the comprehensive influence of multiple factors, especially when considering different seismic wave inputs, long-period seismic waves, and seismic motion characteristics. The research methods are more complex, encompassing advanced methods such as multi-degree-of-freedom systems, time history analysis, and response spectrum methods [44]. Fig. 4 compares the research dimensions and damage index distribution of double-column piers. Abroad, the impact of seismic motion characteristics (such as frequency, duration, and long-period effects) on the vulnerability of bridges is emphasized amidst multiple seismic wave inputs and complex factors. Multi-degree-of-freedom systems and time history analysis are commonly used for in-depth exploration. Modern computational methods tend to favor advanced dynamic analysis, probabilistic methods, and response spectrum methods, applicable to various seismic scenarios, and provide multi-level vulnerability assessment models. Additionally, considering long-term impacts and post-disaster recovery, it emphasizes the long-term seismic effects on bridges and post-disaster recovery strategies, proposing a more comprehensive vulnerability assessment framework. Table 4 shows a comparison of the abstracts of several representative papers [45–47].

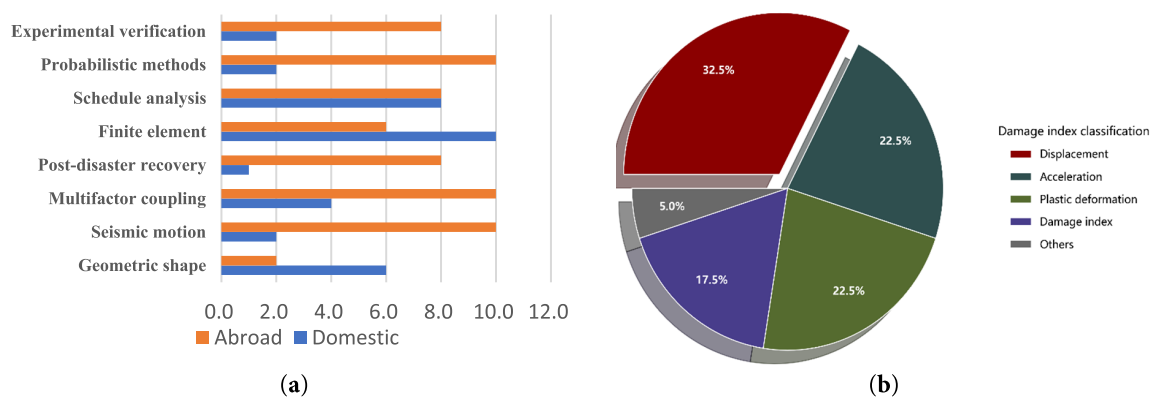


Figure 4: Analysis of vulnerability parameters of double-pier bridges, (a) Comparison of vulnerability across dimensions, (b) Distribution of damage index for double-pier bridges.

Table 4: Comparison of domestic and international research on the vulnerability of double-column piers.

Research Methods	Contribution/Conclusion	Insufficient
Finite Element vibration table Damage Index	Establish a damage assessment model [48]	Lack of diversity, lack of actual seismic wave data
Finite Element Damage model	Focus on the nonlinear response of bridge piers	Parameter analysis is relatively simplified
Schedule analysis, damage index	Optimization of the applicability of the damage index method [49]	Ignore changes in shape and size
Finite element, response spectrum, time history analysis	Evaluation method combining response spectrum method and time history analysis	Insufficient experimental validation

(Continued)

Table 4 (continued)

Research Methods	Contribution/Conclusion	Insufficient
Numerical simulation, time history analysis	Consider the effects of design parameters, soil layer properties, and seismic motion [50]	Lack of actual earthquake data
Schedule analysis, damage prediction method	Combination of Structural Optimization and Damage Assessment	Lack of verification in practical engineering applications
Schedule analysis, finite element simulation [51]	Evaluation Methods for Double-Pier Bridge under Different Earthquake Motions	No comparison of multiple bridge pier columns
Response spectrum method, time history analysis	Seismic performance optimization of bridges with double-column piers	Insufficient consideration of the diversity of bridge pier columns
Damage Index Method, Time History Analysis	Application of Damage Index Method in Vulnerability Assessment	The different nonlinear response effects have not been explored in depth [52]

4.2 Selection of Vulnerability Parameters and Influencing Factors

Displacement is one of the widely used parameters in the vulnerability analysis of bridges. Nielson and DesRoches [50] proposed using displacement as the main parameter for vulnerability assessment, focusing on the impact of different seismic motions on bridge displacement. Studies generally suggest that displacement can offer useful indications of structural deformation, particularly during the nonlinear response phase, where an increase in displacement may signal that the bridge structure is approaching a certain performance threshold. Wu et al. [51] combined displacement with plastic deformation considerations to propose a new displacement based vulnerability assessment method. The displacement response of dual column pier bridges under seismic action is frequently employed to evaluate their seismic capacity. As illustrated in Fig. 4, the vulnerability parameters of double-pier bridges are further analyzed, including (a) comparison of vulnerability across dimensions and (b) distribution of damage index for double-pier bridges. However, displacement itself can only serve as a simplified measure and cannot accurately capture the local damage conditions of bridges under different seismic actions. The limit value of displacement may vary depending on the type of structure and the characteristics of the seismic motion [53–57].

The damage index is a comprehensive parameter commonly used to quantitatively describe the damage state of bridges. Research by Si et al. [54] indicates that the damage index model combines multiple parameters such as displacement, plastic deformation, and crack development, making damage prediction more accurate. However, the calculation of the damage index relies on accurate material models and structural response data, and under seismic excitation, the damage index is significantly influenced by the spectral characteristics of the seismic waves and the complexity of the bridge's own structure. Plastic deformation refers to the permanent deformation of materials that exceeds the elastic limit, and it typically reflects the nonlinear behavior of structures. Wang et al. [55] emphasized the importance of plastic deformation in the damage assessment of bridges in their study, proposing a vulnerability assessment method for double-column pier bridges based on plastic deformation.

Liu et al. [58] explored assessment methods that combine plastic deformation with other damage indicators (such as displacement and damage index), optimizing the evaluation of the seismic performance of bridges. In the vulnerability analysis of double-column pier bridges, plastic deformation can reveal the extent of damage to the structure during significant earthquakes, particularly the plastic response of the pier columns and joints. However, as a nonlinear parameter, the analysis of plastic deformation is relatively complex and computationally intensive. Additionally, the contribution of plastic deformation from different parts to overall damage varies, necessitating regional assessments.

The geometric form of the pier columns, Liu et al. [59] proposed the impact of geometric factors (such as column spacing, height, cross-sectional shape, etc.) on the vulnerability analysis of bridges and conducted a systematic comparison, indicated that geometric parameters such as the height of the pier columns, cross-sectional shape, and design of longitudinal reinforcement significantly affect the response of bridges under strong earthquakes. Different geometric shapes of pier columns can lead to different stress distributions, thereby affecting the degree of structural damage. The research by Dong et al. [60] found that optimizing pier column design can effectively reduce the vulnerability of bridges, especially in the performance during large and near earthquakes. Tall bridge piers or shorter pier columns can lead to different vibration characteristics, affecting the overall stability and vulnerability of the bridge. The effect of the height of the pier and the seismic period as shown in Fig. 5a. Feng et al. [56] discussed the impact of pier column geometry on the seismic performance of bridges and proposed a damage assessment model that combines geometric parameters with seismic motion characteristics.

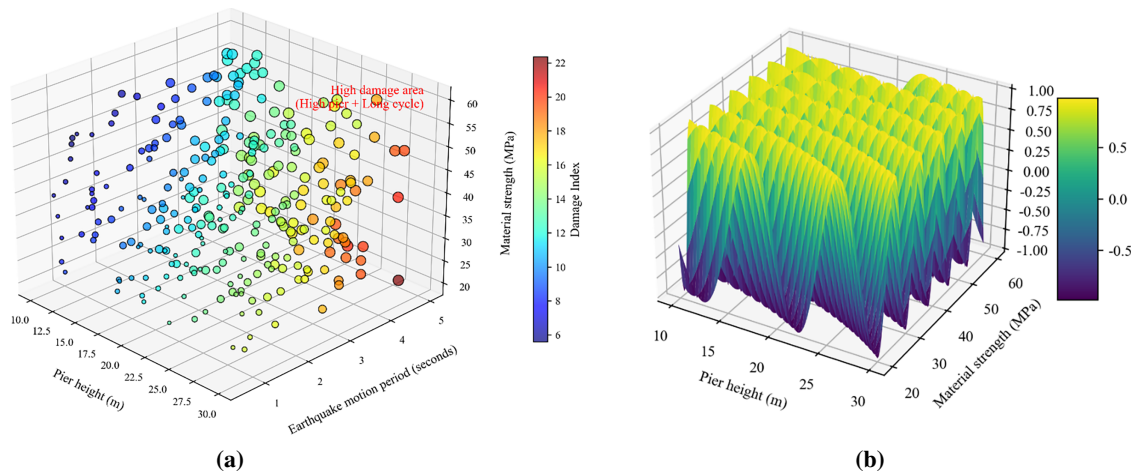


Figure 5: Interaction between seismic motion and various parameters. (a) Three-dimensional damage distribution map, (b) Coupling effects of seismic motion.

The material characteristics of bridge double pier columns, including reinforced concrete, prestressed concrete, and steel structures, affect their mechanical response during earthquakes, as shown in Fig. 5b. The strength, toughness, and seismic performance of materials are key factors determining the seismic performance of bridges. Zhang et al. [61] demonstrated that using high-strength concrete or steel with excellent material properties can significantly enhance the seismic capacity of bridges; therefore, the improvement of material characteristics is an important consideration in design optimization. Rashid and Nishio [62] pointed out in their study that the nonlinear effects of materials on bridge damage cannot be ignored and proposed corresponding analytical methods.

The design of the joints between the bridge pier and the bridge girder plays an important role in the overall seismic performance. Rashid and Nishio [62] proposed that optimizing joint design and using high-strength reinforced concrete can reduce post-earthquake damage to bridges, especially under the influence of strong earthquakes, where optimized joint design can significantly mitigate damage. Fu et al. [53] highlighted the importance of joint design on the vulnerability of double-column pier bridges in their study and conducted numerical simulations for different joints. Reasonable joint design can effectively reduce damage under seismic actions. Liu et al. [58] explored the impact of joint design on vulnerability assessment under different seismic motions and proposed optimization suggestions for joint design. The type of joint (such as fixed joints, sliding joints, etc.) and connection methods (such as rebar configuration, bonding methods, etc.) have a significant impact on structural performance. The complexity of joints and the combination of various connection methods make the influence of joint design on vulnerability assessment quite complex, and precise modeling and analysis of joint design are often challenging.

Different types of seismic motions have significant differences in their response to bridge structures. The study by Qin et al. [63] indicates that long-period seismic motions have a more pronounced effect on double-column pier bridges, particularly at the joints and connections of the pier columns, which may lead to greater plastic deformations. For strong earthquakes, the contributions of displacement and plastic deformation parameters to vulnerability are more significant. The type of seismic motion determines the response characteristics of the bridge, making it crucial for vulnerability assessment; factors such as the spectrum of the seismic motion, duration, and direction of the seismic waves can all affect the response of the bridge structure. The diversity of seismic motion types makes it challenging to ensure the accuracy of vulnerability assessments, and different seismic waves may have substantial variations in their effects on bridges.

However, the differences in the weights of various factors and the choice of assessment methods vary across different studies, and most models rely on support from experiments and numerical analysis, Table 5 summarizes the vulnerability parameters across different dimensions. Therefore, multi-factor comprehensive analysis and model validation are important directions for future vulnerability assessment research.

Table 5: Comparison of the fragility parameters of double column piers.

Vulnerable Parameters	Experimental/Simulation Methods	Contribution	Literature Suggested Specific Techniques
Displacement [64–67]	Finite element analysis, experimental research, time history analysis	Quantified displacement impact on double-column pier vulnerability.	Probabilistic seismic demand models with expanded ground motion suites.
Damage Index [68–70]	Finite element analysis, time history analysis, probabilistic methods	Proposed vulnerability assessment method quantifying seismic impact.	Multiple damage indices within incremental dynamic analysis frameworks.
Plastic Deformation [71–74]	Time history analysis, finite element, probabilistic analysis, shaking table test	Studied plastic deformation effects on seismic resistance and vulnerability.	Refined nonlinear models with bar slip and low-cycle fatigue effects.

(Continued)

Table 5 (continued)

Vulnerable Parameters	Experimental/Simulation Methods	Contribution	Literature Suggested Specific Techniques
Pillar Geometry [75–77]	Finite element analysis, time history analysis, soil-structure interaction analysis	Examined pier geometry influence on bridge vulnerability.	Expanded parametric studies with probabilistic demand models.
Material Properties [78,79]	Finite element, experimental research, time history analysis	Analyzed material strength and stiffness contributions to vulnerability.	Advanced constitutive models with sensitivity analysis.
Joint Design [80,81]	Finite element analysis, time history analysis, shaking table test	Investigated joint design impact and proposed improved schemes.	High-fidelity joint modeling within probabilistic frameworks.
Types of Seismic Motion [79–82]	Schedule analysis, seismic motion simulation experiments, finite element analysis	Proposed vulnerability methods for different seismic motion types.	Vector-valued intensity measures with near-fault and long-duration records.

4.3 Parameter Interactions and Coupling Effects

In the vulnerability analysis of double-column pier bridges, the interaction and coupling effects between vulnerability parameters play a crucial role in the seismic resistance of the structure. Research shows that factors such as pier geometry, bridge material properties, joint design, and seismic motion characteristics are interwoven, affecting the overall nonlinear behavior of the bridge, which in turn influences the vulnerability assessment results, as shown in Fig. 6.

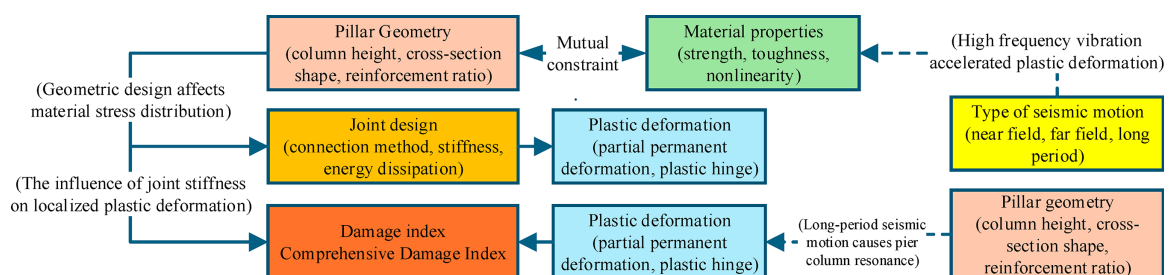


Figure 6: Coupling effects between parameters.

Firstly, the height of the pier plays an important role in affecting the overall performance and vulnerability of the bridge. Pan et al. [83] confirmed that taller piers, under strong seismic action, are prone to significant plastic deformation due to bearing larger seismic forces, leading to exacerbated damage to the bridge. This phenomenon is particularly evident in cases of low-frequency seismic motion, as low-frequency vibrations make the nonlinear response of high pier bridges more pronounced. Furthermore, research by Zhang et al. [65] also indicates a significant coupling effect between pier height and the nonlinear behavior of the bridge, where increased pier height may result in larger displacements during the nonlinear phase,

thereby increasing the damage index. Secondly, the characteristics of seismic motion also have a significant impact on vulnerability parameters.

Different types of seismic motion, particularly near-field and far-field earthquakes, tend to exert distinct influences on bridge structures. Near-field seismic waves are often associated with more intense vibrations and relatively brief durations, which may contribute to accelerated accumulation of plastic deformation and could lead to an elevated damage index under certain conditions. In this context, the interplay between pier height and seismic motion characteristics appears to be of considerable importance. Taller piers may exhibit heightened susceptibility to structural distress when subjected to near-field excitations, and during strong seismic events, the corresponding increases in displacement and plastic deformation could potentially result in more pronounced damage outcomes.

Material properties are also an important factor affecting vulnerability assessment. It has been shown that the yield point and stiffness of the material directly determine the degree of plastic deformation of reinforced concrete bridges when subjected to strong earthquakes. Higher material stiffness usually implies less plastic deformation, but in some cases, increased material stiffness may lead to an overconcentration of the bridge's load-carrying capacity, resulting in increased localized damage. Therefore, the interaction between the nonlinear behavior of materials and the geometry of piers and columns should not be neglected, and they have a coupling effect on the susceptibility of bridges under strong seismic action. In addition, the design of joints has an important effect on the nonlinear response of bridges. Romero and Moustafa [84] showed that the cracking and yielding behavior in the joint region can exacerbate the nonlinear behavior of bridges, especially under strong seismic effects, and the defective or insufficient design of joints may lead to the rapid development of bridge damage.

In summary, the vulnerability analysis of double-column pier bridges must consider the interaction of multiple factors. Factors such as the height of the pier columns, the material properties of the bridge, joint design, and seismic motion characteristics are coupled under different conditions, producing complex effects on the bridge's nonlinear response and damage index. Although existing research has provided valuable quantitative analysis of the interactions between these parameters, further deepening the understanding of the coupling effects among various factors is still needed, especially regarding multidimensional interactions under actual seismic motion conditions.

5 Summary and Outlook

The recoverable function of bridges has become a key direction to enhance the seismic resilience of infrastructure and reduce the recovery time after disasters. As a common structural form, the study of the recoverable function of double-column piers aims to enhance the self-repairing ability of bridges in disasters such as earthquakes and ensure rapid return to use after disasters. By introducing new technologies such as shape memory alloys, self-repairing concrete, and smart materials, as shown in Fig. 7, bridges are able to recover their functions quickly after being hit by earthquakes, which reduces transportation disruptions and socioeconomic losses [85–87]. The national emphasis on green, smart, and sustainable infrastructures has also promoted the research and application of restorable functions. Future investigations may also benefit from a more structured methodological framework that systematically classifies vulnerability assessment approaches into deterministic, probabilistic, and machine learning-based categories, as well as according to the primary parameters employed, such as engineering demand parameters, intensity measures, and damage indices, thereby facilitating more rigorous comparisons and the integration of recoverable function concepts within probabilistic vulnerability and resilience frameworks. With the continuous progress of material science and intelligent technology, the seismic toughness and post-disaster recovery capacity of bridges will be further improved in the future, which will in turn effectively reduce the repair time and resource

consumption [88]. Future research efforts should systematically address several critical areas. First, the quantitative incorporation of smart material hysteretic characteristics into probabilistic vulnerability frameworks is needed to explicitly refine fragility curves and residual displacement forecasts. Second, standardized analytical protocols must be developed to assess parameter coupling effects on cumulative structural damage under multi-hazard conditions. Third, recoverable function indicators should be integrated into resilience-oriented design methodologies that account for both repair duration and life cycle expenditures. Fourth, high-fidelity numerical simulation techniques require advancement to accurately represent the nonlinear behavior of prefabricated connection details subjected to near-fault pulse-type and long-duration far-field ground motions [89].

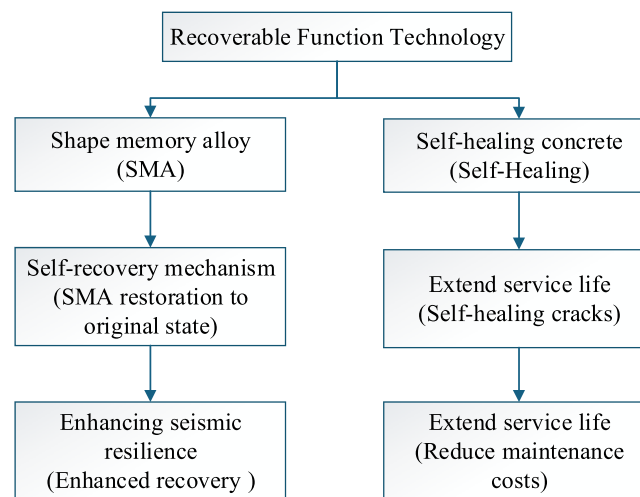


Figure 7: Recoverable function technology.

5.1 Current Status of Domestic and International Research on Recoverable Functions

Domestic research mainly focuses on the recovery capacity of bridges after earthquake disasters, especially through the use of new materials and intelligent technologies to enhance the recoverability of bridges. For example, Benshams et al. [90] studied the application of Shape memory alloys (SMA) in double-column pier bridges, proposing that shape memory alloys can effectively restore bridge deformation through external excitation, exhibiting good self-repair characteristics and significantly improving the seismic recovery capacity of bridges. As shown in Fig. 8, meanwhile, Qian et al. [91] demonstrated through experimental research that the application of self-repairing concrete in bridge piers can effectively repair micro-cracks, extend the service life of bridges, and improve seismic toughness.

In addition, some domestic scholars have proposed post-disaster recovery models for bridges based on Structural Health Monitoring (SHM) technology. Tsiavos and Oswald [92] proposed a damage assessment and repair decision model based on real-time monitoring data, which can timely assess the damage level of bridges and guide repair work after an earthquake. With the national focus on green infrastructure construction, Lu et al. [93] pointed out that future research on the recoverable functionality of domestic bridges should emphasize the integration of green environmental protection and intelligent technology, such as the combined application of smart sensors and self-healing materials, to achieve self-healing and rapid recovery of bridges.

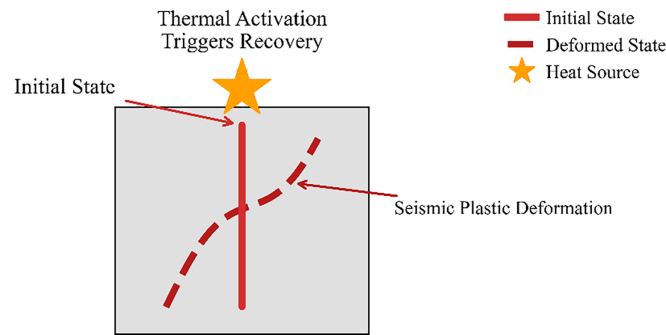


Figure 8: SMA self-resetting me.

Research abroad started relatively early, especially in the United States, Japan, and Europe, where the study of the recoverable functionality of bridges has gradually entered the practical application stage. Zhao et al. [94] proposed that shape memory alloys can not only improve the seismic performance of bridges but also restore structural deformations through external excitation after an earthquake, significantly reducing repair time. Research in the United States on self-healing concrete has also made breakthroughs; Chortis et al. [95] found through experiments that self-healing concrete has the ability to self-repair cracks, making it particularly suitable for application in bridge piers, significantly enhancing the post-disaster recovery capability of bridges. In addition, Japanese researchers mainly focus on the combined application of smart materials and structural health monitoring systems. Warsi et al. [96] proposed that by integrating self-healing coatings with sensor systems, bridges can not only achieve self-repair but also identify structural damage in advance through real-time monitoring, providing accurate data support for the restoration of bridges. European research, on the other hand, emphasizes the combination of materials and construction techniques, proposing the application of various new high-performance materials, such as fiber-reinforced polymers (FRP) and nanomaterials. The introduction of these materials significantly enhances the recovery capacity of bridges and shortens the post-disaster repair time.

5.2 Contribution of New Materials and Technologies to the Recoverable Function of Double-Column Piers

New materials and technologies not only enhance the seismic capacity of bridges, but also accelerate the post-earthquake recovery process and reduce the repair cost. Shape memory alloys (SMAs) have become an important material for enhancing bridge recovery due to their ability to return to their original state after earthquakes [97]. Self-healing materials such as self-healing concrete automatically repair microcracks through chemical reaction or microbial action, as in Fig. 9, which enhances long-term durability and shortens post-disaster repair time. Fiber-reinforced composites (FRPs) have been widely used in bridge reinforcement and rehabilitation due to their high strength and light weight, especially in improving seismic performance and recovery. The combination of smart materials and structural health monitoring (SHM) technology provides dual guarantees of real-time monitoring and damage repair for double-column pier bridges, enabling rapid post-disaster evaluation and repair. Ultra-high performance concrete (UHPC) plays a key role in enhancing seismic capacity and shortening the rehabilitation cycle with its excellent mechanical properties and durability. Meanwhile, future developments in probabilistic vulnerability modeling and computational methods, including refined finite element approaches and advanced time history analysis techniques, are expected to further strengthen the analytical foundation for assessing and optimizing such recovery solutions. Adaptive structural technology can effectively reduce earthquake-induced damage by dynamically adjusting bridge response and further enhancing recoverability. Nanomaterials enhance seismic recovery by virtue of their excellent crack resistance and durability. Multi-material composite structures

combining shape memory alloys and self-healing concrete significantly enhance the ability of double-column pier bridges to recover rapidly after earthquakes. Finally, the application of artificial intelligence technology in bridge recovery provides new ideas for decision support, and through deep learning and machine learning algorithms, precise control and efficient repair can be realized in the post-disaster recovery process [98,99]. Overall, the application of new materials and technologies not only improves the seismic performance of double-column pier bridges but also provides a more efficient and sustainable solution for post-disaster bridge rehabilitation, while ongoing advances in computational vulnerability analysis continue to refine the tools available for evaluating and guiding such innovations.

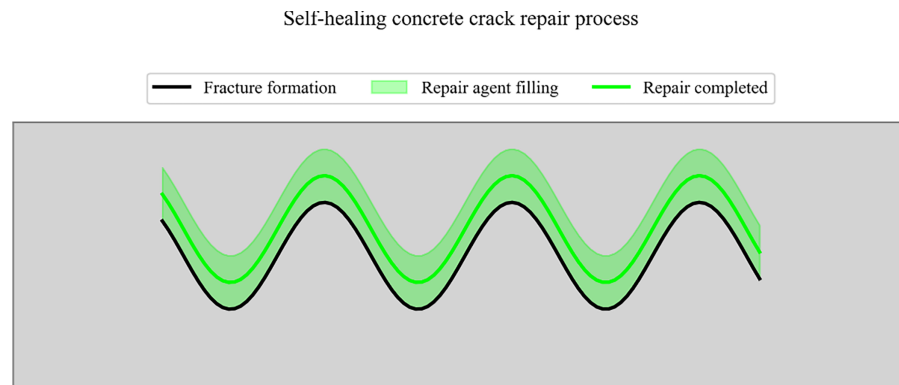


Figure 9: Self-healing concrete mechanisms.

Acknowledgement: The authors would like to thank Tutor Yifang Huang at the Training Platform of Construction Engineering at the Polytechnic Institute of Zhejiang University for their help in the bridge pier test.

Funding Statement: This research was supported by the Zhejiang Provincial Natural Science Foundation of China under Grant No. LTGG23E080001.

Author Contributions: The authors confirm contribution to the paper as follows: Conceptualization, writing—review and editing, project administration: Xiao-Hui Yu; writing—original draft preparation: Yu-Xuan Ding; investigation: Cheng-Quan Wang, Rui-Rui Qian, Zi-Hao Ren, Zhi-Hao Zhai, Jing-Yao Liu. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The authors confirm that the data supporting the findings of this study are available within the article.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zeng X, Xie BX, Jiang SF, Wang P, Lin X. Seismic performance of reinforced concrete double-column piers in the longitudinal direction of the bridge under the combination of compression, bending, shear, torsion. *Structures*. 2025;76:108921. doi:10.1016/j.istruc.2025.108921.
2. Rabi RR, Vailati M, Monti G. Effectiveness of vibration-based techniques for damage localization and lifetime prediction in structural health monitoring of bridges: a comprehensive review. *Buildings*. 2024;14(4):1183. doi:10.3390/buildings14041183.
3. Wu L, Jiang J, Ling L, Wang Z, Wang Y, Liu G, et al. Seismic fragility analysis of double-column bridge piers under freeze–thaw cycles. *Buildings*. 2025;15(18):3358. doi:10.3390/buildings15183358.

4. Zhang Y, Xiao F, Badar J. Influence of straining beams on the seismic fragility of double-column bridge piers. *Stavební Obzor Civ Eng J*. 2019;28(1):32–44. doi:10.14311/cej.2019.01.0004.
5. Rahmat Rabi R, Monti G. Fragility curves of hollow-core bridge piers for territorial risk studies using closed-form equations. *Structures*. 2024;61:105966. doi:10.1016/j.istruc.2024.105966.
6. Zhang G, Su S, Han Q, Xu K, Li Z, Du X. Experimental and numerical investigation of seismic performance of prefabricated double-column piers used in accelerated bridge construction. *Eng Struct*. 2023;293(1):116688. doi:10.1016/j.engstruct.2023.116688.
7. Wang J, Jin C, Bao Y, Hong Y, Xie W. Seismic performance assessment of existing low-ductility reinforced concrete double-column bridge piers retrofitted with buckling-restrained braces. *Soil Dyn Earthq Eng*. 2025;188(12):109051. doi:10.1016/j.soildyn.2024.109051.
8. Xiong J, Chen X. Seismic performance of double-column tall pier bents using fusing connections. *Soil Dyn Earthq Eng*. 2023;170:107924. doi:10.1016/j.soildyn.2023.107924.
9. Xie W, Wang J, Bao Y, Sun L. Theoretical studies and verification on tall RC two-column piers with BRBs: numerical simulations and shaking table tests. *Eng Struct*. 2024;304(3):117683. doi:10.1016/j.engstruct.2024.117683.
10. Upadhyay A, Pantelides CP. Seismic analysis of bridge with buckling-restrained brace posttensioned concrete pier. *Earthq Engng Struct Dyn*. 2025;54(1):227–45. doi:10.1002/eqe.4257.
11. Hong Y, Ye L, Xie W. Seismic fragility and resilience improvement of conventional bridges supported by double-column piers utilizing shear links. *Structures*. 2023;57(09):105309. doi:10.1016/j.istruc.2023.105309.
12. Ye L, Wang Y, Xie W. Seismic fragility and loss assessment on earthquake-resilient double-column tall piers with shear links subjected to far-field and near-fault ground motions. *Structures*. 2022;45(11):1774–87. doi:10.1016/j.istruc.2022.10.031.
13. Li X, Zhang Z, Zhou T, Xiao Y, Sun Y. Hysteretic behavior of post-tensioned precast segmental CFT double-column piers. *Earthq Eng Eng Vib*. 2023;22(3):747–62. doi:10.1007/s11803-023-2196-6.
14. Wang DS, Sun ZG, Guo X, Li XL, Huo Y. Lessons learned from Wenchuan seismic damages and recent research on seismic design of highway bridges. *J Highw Transp Res Dev*. 2011;28(10):44–53. (In Chinese).
15. Zhou Y, Ping T, Gong S, Zhu Y. An improved defining parameter for long-period ground motions with application of a super-tall building. *Soil Dyn Earthq Eng*. 2018;113(2):462–72. doi:10.1016/j.soildyn.2018.06.018.
16. Rahnavard R, Thomas RJ. Numerical evaluation of steel-rubber isolator with single and multiple rubber cores. *Eng Struct*. 2019;198(8):109532. doi:10.1016/j.engstruct.2019.109532.
17. Deviprasad BS, Saseendran R, Dodagoudar GR. Fragility analysis of bridge pier supported on rocking shallow foundation under earthquake loading. *Bull Earthq Eng*. 2022;20(12):6901–17. doi:10.1007/s10518-022-01463-3.
18. Xie W, Sun L. Experimental and computational assessment of shear beams as earthquake resilient measure for double-column piers supported by pile-group. *Eng Struct*. 2021;242(3):112509. doi:10.1016/j.engstruct.2021.112509.
19. Lu G, Zhang B, Li Z, Su J, Hui Y, Wu G. An advanced ANN-based framework for seismic damage prediction and fragility analysis of reinforced concrete double-column piers in highway bridge networks. *Structures*. 2025;78(4):109233. doi:10.1016/j.istruc.2025.109233.
20. Pang Y, Wei K, Wang J, Zhang S. An efficient and accurate fragility approach for seismic performance assessment of structures. *Earthq Eng Resil*. 2023;2(4):403–17. doi:10.1002/eer2.64.
21. Zhou Y, Gao C, Yang S, Guo W, Jiang L. Seismic fragility analysis of reinforced concrete simply supported girder bridges resting on double-column piers for high speed railway. *Buildings*. 2024;14(10):3072. doi:10.3390/buildings14103072.
22. Dong HH, Li H, Du XL. Fragility analysis of the double-column bent with the SCEB under near-field pulse-like ground motions in transverse direction. *J Beijing Univ Technol*. 2023;49(5):532–46. (In Chinese).
23. Zhou X, Xu T, Liu J, Wang X, Chen YF. Seismic performance of concrete-encased column connections for concrete filled thin-walled steel tube piers. *Eng Struct*. 2022;269(2):114803. doi:10.1016/j.engstruct.2022.114803.
24. Seify Asghshahr M, Afsar Dizaj E, Ghasemi A. Optimal intensity measures for seismic fragility assessment of corrosion-damaged RC bridge piers. *Bull Earthq Eng*. 2024;22(11):5673–704. doi:10.1007/s10518-024-01974-1.
25. Sandıkkaya MA, Akkar S, Kale Ö, Yenier E. A simulation-based regional ground-motion model for Western Türkiye. *Bull Earthquake Eng*. 2023;21(7):3221–49. doi:10.1007/s10518-023-01658-2.

26. Li C, Kunnath SK, Zhao Y. A new framework for ground motion selection for structural seismic assessment. *Eng Struct.* 2023;285(3):116055. doi:10.1016/j.engstruct.2023.116055.
27. Dehghanpoor A, Thambiratnam D, Zhang W, Dong Y, Kargar M, Chan T, et al. Performance assessment of reinforced concrete bridges under coupled horizontal and vertical ground motions using fragility surfaces. *J Earthq Eng.* 2024;28(10):2801–23. doi:10.1080/13632469.2024.2308612.
28. Jiang J, Sorensen AD. Finite element analysis of reinforced concrete bridge piers under sequential vehicle impact and seismic loads: case study. *Transp Res Rec J Transp Res Board.* 2025;2679(10):430–48. doi:10.1177/03611981251342232.
29. Diao YC, Li C, Li HN. Development of a new seismic performance assessment method for bridges considering uncertainties in the entire process of seismic wave propagation and structural dynamic response: a case study of precast segmental pier bridges. *Bull Earthq Eng.* 2026;24(5):1–33. doi:10.1007/S10518-026-02383-2.
30. Yang Z, Dong H, Han Q, Du X. Residual drift ratio evaluation of double-column RC bridges with additional self-centering energy dissipation dampers under near-fault ground motions. *Earthq Spectra.* 2025;41(3):2225–54. doi:10.1177/87552930251337249.
31. Qin H, Milani G, Bi K, Dong H, Du X. A novel cable-pulley based self-centering energy dissipation (CP-SCED) brace for seismic induced damage mitigation of RC double-column bridge piers. *Eng Struct.* 2025;333(3):120130. doi:10.1016/j.engstruct.2025.120130.
32. Yao Y, Zhu B, Jiang N, Yang Y. Experimental study on the dynamic response of double-column viaduct pier under the action of blasting vibration. *Structures.* 2025;76(6):108939. doi:10.1016/j.istruc.2025.108939.
33. Kong W, Yang S, Wang S, Liu Z, Zhang R, Zhong W, et al. On dynamic response and damage evaluation of bridge piers under far-field explosion loads. *Structures.* 2023;51(10):985–1003. doi:10.1016/j.istruc.2023.03.030.
34. Luo Q, Dai F, Liu Y, Gao M, Li Z, Jiang R. Seismic performance assessment of velocity pulse-like ground motions under near-field earthquakes. *Rock Mech Rock Eng.* 2021;54(8):3799–816. doi:10.1007/s00603-021-02475-2.
35. Dong H, Ma R, Bi K, Han Q, Su C, Du X. Experimental study on the seismic performance of self-centering braced double-column rocking bent. *Earthq Eng Struct Dyn.* 2025;54(3):885–904. doi:10.1002/eqe.4282.
36. Si X, Wen J, Zhang G, Jia Z, Han Q. Seismic performance of precast double-column pier with UHPC-filled socket connections. *Eng Struct.* 2023;285(6):115618. doi:10.1016/j.engstruct.2023.115618.
37. Qin H, Bi K, Dong H, Han Q, Du X. Shake table tests on RC double-column bridge piers with self-centering energy dissipation braces. *J Bridge Eng.* 2023;28(8):04023049. doi:10.1061/jbenf2.beeng-6069.
38. Nguyen HV, Phan HN, Pham DH, Quinci G, Paolacci F. Portfolio-scale seismic fragility of RC bridge columns with series-distributed neural networks. *Int J Disaster Risk Reduct.* 2026;132(4):105955. doi:10.1016/j.ijdrr.2025.105955.
39. Zhou L, Li X, Yan Q. Dynamic response and vulnerability analysis of pier under near-field underwater explosion. *Eng Fail Anal.* 2024;155:107749. doi:10.1016/j.engfailanal.2023.107749.
40. He H, Zhou J, Xu L, Xiang Z, Zhou Y, Shi J, et al. Optimization of a novel lateral energy dissipation system for cable-stayed bridge with short piers based on seismic vulnerability analysis. *Structures.* 2024;70:107700. doi:10.1016/j.istruc.2024.107700.
41. Dong H, Feng W, Zheng Z, Han Q, Du X. Experimental investigation on failure mechanism and hysteresis behavior of RC single- and double-column piers. *J Bridge Eng.* 2024;29(12):04024094. doi:10.1061/jbenf2.beeng-6912.
42. Jiang L, Ge CY, Zhou PC, Sun ZG, Liu JJ, Liu YH, et al. Numerical study on seismic performance of rocking self-centering (RSC) bridge piers under bidirectional excitation. *Int J Str Stab Dyn.* 2025;25(5):2550041. doi:10.1142/s0219455425500415.
43. Cui H, Shao C. Experimental study on seismic performance of circular hollow piers with low-to-medium shear-span ratio in high-seismic intensity regions. *Structures.* 2026;87(4):111767. doi:10.1016/j.istruc.2026.111767.
44. Liu Z, Zhou H, Zhao X, Zhao W, Guo A. Physics-enhanced machine learning surrogate modelling for real-time seismic fragility assessment of reinforced concrete bridges. *Eng Struct.* 2026;348:121772. doi:10.1016/j.engstruct.2025.121772.
45. Poorahad AP, Shiravand MR. Data-driven multi-criteria framework for the seismic and post-earthquake performance assessment of corroded RC bridge piers. *Structures.* 2025;82:110535. doi:10.1016/j.istruc.2025.110535.

46. Dangol I, Pantelides CP. Seismic analysis of posttensioned and hybrid bridge bents with buckling restrained braces. *J Bridge Eng.* 2023;28(2):04022146. doi:10.1061/jbenf2.beeng-5764.
47. Abdulkareem Z, Oukaili N, Al-Mahaidi R. Efficiency of self-prestressing Fe-based shape memory alloys on shear strengthening of high-strength RC beams: experimental and numerical investigation. *Structures.* 2024;63(1):106317. doi:10.1016/j.istruc.2024.106317.
48. Afsar Dizaj E, Kashani MM. Influence of ground motion type on nonlinear seismic behaviour and fragility of corrosion-damaged reinforced concrete bridge piers. *Bull Earthq Eng.* 2022;20(3):1489–518. doi:10.1007/s10518-021-01297-5.
49. Biondini F, Camnasio E, Titi A. Seismic resilience of concrete structures under corrosion. *Earthq Eng Struct Dyn.* 2015;44(14):2445–66. doi:10.1002/eqe.2591.
50. Nielson BG, DesRoches R. Analytical seismic fragility curves for typical bridges in the central and southeastern United States. *Earthq Spectra.* 2007;23(3):615–33. doi:10.1193/1.2756815.
51. Wu J, Chen S, van de Lindt JW. Fatigue assessment of slender long-span bridges: reliability approach. *J Bridge Eng.* 2012;17(1):47–57. doi:10.1061/(asce)be.1943-5592.0000232.
52. Jin C, Chen H, Cheng Y, Xie W. Experimental investigation and numerical simulation of seismic performance of rectangular hollow-section UHPC double-column piers without stirrups. *Eng Struct.* 2026;358(2):122634. doi:10.1016/j.engstruct.2026.122634.
53. Fu J, Wan S, Zhou P, Shen J, Loccufier M, Dekemele K. Effect of magnetic-spring bi-stable nonlinear energy sink on vibration and damage reduction of concrete double-column piers: experimental and numerical analysis. *Eng Struct.* 2024;303(1):117517. doi:10.1016/j.engstruct.2024.117517.
54. Si J, Dong S, Liu Z, Qiao Y, Wang Y, Sun W, et al. Experimental study and finite element analysis on the flexural performance of predamaged concrete beams strengthened with PET straps. *Structures.* 2026;84(1):111025. doi:10.1016/j.istruc.2025.111025.
55. Wang S, Sun Z, Wang D. Analysis and verification of load-deformation response for rocking self-centering bridge piers. *Sustainability.* 2023;15(10):8257. doi:10.3390/su15108257.
56. Feng W, Zhang Z, Sun J, Ci M, Wang S. Seismic performance and damage mechanism of RC double-column pier structure with triple coupling beams. *Int J Civ Eng.* 2024;22(6):1081–97. doi:10.1007/s40999-024-00945-6.
57. Liu Y, Yang B, Li B, Xiao SN, Zhu T, Yang G, et al. Experimental and numerical investigation of the design strategy of new anticollision posts for a typical railway vehicle. *Int J Rail Transp.* 2022;10(6):772–99. doi:10.1080/23248378.2021.2002737.
58. Liu H, Liu M, Yang X, Liu J. Vulnerability analysis of design usage concrete structures considering coupled effects of carbonation rate and cumulative seismic damage. *Sādhanā.* 2025;50(2):89. doi:10.1007/s12046-025-02742-w.
59. Liu M, Yuan G, Sun W, Shu Q, Zhao Z, Lu L. Experimental and numerical investigation on the seismic performance of RC squat shear walls with single post-opening reinforced by steel plates. *Eur J Environ Civ Eng.* 2024;28(1):53–79. doi:10.1080/19648189.2023.2200464.
60. Dong H, Hu X, Du X, Wen J, Han Q. Seismic performance of RC bridges with double-column medium height bents retrofitted with SCEBs under near-field ground motions. *Bull Earthq Eng.* 2024;22(5):2615–41. doi:10.1007/s10518-024-01863-7.
61. Zhang ZL, Li X, Zhang CX, Sun YS. Seismic behavior of precast CFST double-column piers with various connection types. *J Constr Steel Res.* 2024;215(8):108546. doi:10.1016/j.jcsr.2024.108546.
62. Rashid M, Nishio M. Energy-based fragility assessment of reinforced concrete bridges considering cumulative seismic demand under mainshock-aftershock sequences. *Bull Earthq Eng.* 2025;23(15):6939–69. doi:10.1007/s10518-025-02300-z.
63. Qin H, Dong H, Milani G, Ma R, Bi K, Du X. Multi-objective optimization design method of RC double-column bridge piers with cable-pulley based self-centering energy dissipation (CP-SCED) braces. *Eng Struct.* 2025;343(1):121171. doi:10.1016/j.engstruct.2025.121171.
64. Mo R, Chen L, Chen Y, Xiong C, Zhang C, Chen Z, et al. Prediction and correlations estimation of seismic capacities of pier columns: extended Gaussian process regression models. *Struct Saf.* 2024;109(2):102457. doi:10.1016/j.strusafe.2024.102457.

65. Zhang Y, Xie R, Zuo X, Fan W. Experimental and numerical investigation of post-earthquake recoverability of a novel precast segmental double-column pier. *Eng Struct.* 2025;343(8):121052. doi:10.1016/j.engstruct.2025.121052.
66. Zhong H, Guo J, Dang X, Deng X, Yuan W, Wang Z. Seismic performance of precast double-column rock-ing piers with U-shaped tendons and stiffening steel shoes: experimental and numerical study. *Eng Struct.* 2025;330(5):119894. doi:10.1016/j.engstruct.2025.119894.
67. Chen L, Chen L, Zhou J. Seismic fragility analysis of girder bridges under mainshock-aftershock sequences based on input-output hidden Markov model. *Earthq Eng Struct Dyn.* 2024;53(11):3469–88. doi:10.1002/eqe.4182.
68. Stefanidou S, Markogiannaki O, Mikes I, Fragiadakis M. Fragility analysis framework for bridges subjected to successive natural hazards. *Struct Eng Int.* 2024;34(1):45–54. doi:10.1080/10168664.2023.2273464.
69. Antonopoulos C, Tubaldi E, Carbonari S, Gara F, Dezi F. Dynamic behaviour and seismic response of scoured bridge piers. *Infrastructures.* 2025;10(4):75. doi:10.3390/infrastructures10040075.
70. Zhang Y, Tang W, Liu C, Fan W, Zhao S. Damage mechanism and assessment of precast double-column bridge piers under blast impact. *Eng Fail Anal.* 2024;158(2):108007. doi:10.1016/j.engfailanal.2024.108007.
71. Zhuang YC. Seismic damage inference and post-earthquake residual capacity evaluation of RC structures [dissertation]. Beijing, China: Tsinghua University, 2024. (In Chinese).
72. Todorov B, Billah AHMM. Seismic fragility and damage assessment of reinforced concrete bridge pier under long-duration, near-fault, and far-field ground motions. *Structures.* 2021;31(4):671–85. doi:10.1016/j.istruc.2021.02.019.
73. Li T, Ji J, Zhang S, Liu J, Sun L. Seismic resilience evaluation method of bridge considering restoration process. *KSCE J Civ Eng.* 2026;30(5):100492. doi:10.1016/j.kscej.2025.100492.
74. Su J, Li J, Chu S, Wu D, Ma J, Li ZX. Assessment of seismic performance for ultra-high performance concrete (UHPC) retrofitted RC bridge piers with height-varying corrosion: a lifetime perspective. *Eng Struct.* 2025;339(2):120693. doi:10.1016/j.engstruct.2025.120693.
75. Atkins J, Hajializadeh D, Iqbal W, Soleimani F. Beyond fragility: physics-driven neural surrogates for seismic resilience prediction of bridges. *Front Built Environ.* 2026;12:1756908. doi:10.3389/fbuil.2026.1756908.
76. Sun J, Xu W, Tan Z. Seismic resilience assessment of the hybrid bridge pier based on fragility analysis. *Int J Steel Struct.* 2024;24(2):324–38. doi:10.1007/s13296-024-00818-7.
77. Djemai MC, Bensaibi M, Halfaya FZ. The effect of type and height of piers on the seismic behavior of reinforced concrete bridges. *Int J Eng Res Afr.* 2019;41:79–87. doi:10.4028/www.scientific.net/jera.41.79.
78. Lu C, Long X, Ma Y, Gu X. Rapid seismic response prediction model of bridges with small-sample data based on cluster and multi-level feature fusion deep learning algorithms. *Eng Appl Artif Intell.* 2026;171(8):114264. doi:10.1016/j.engappai.2026.114264.
79. Zhu Z, Li Y, Ma C. Quasi-static cyclic tests and parametric analysis on the seismic performance of partial precast bridge columns. *KSCE J Civ Eng.* 2023;27(10):4288–99. doi:10.1007/s12205-023-0322-7.
80. Wang T, Han Q, Wen J, Wang L. Analysis of the effect of mainshock-aftershock sequences on the fragility of RC bridge columns. *Buildings.* 2022;12(10):1681. doi:10.3390/buildings12101681.
81. Wang B, Ye Y, Song G, Chen B, Chen X, Hu S. Identification and analysis of the offshore near-fault pulse ground motion and its influence on the seismic response of bridge piers. *Mar Struct.* 2026;107(1):104013. doi:10.1016/j.marstruct.2026.104013.
82. Song L, Wei M, Zhang X, Liu K, Yang H. Seismic performance of concrete-encased CFST column to exterior wide-flat beam joint. *Structures.* 2026;85(8):111078. doi:10.1016/j.istruc.2026.111078.
83. Pan H, Qi M, Guo J, Guo B, Chen P. Experimental and numerical studies on seismic performance of damaged RC bridge columns repaired using different jacketing materials. *Soil Dyn Earthq Eng.* 2026;207(4):110279. doi:10.1016/j.soildyn.2026.110279.
84. Romero AJ, Moustafa MA. Shake table tests of economical precast ultra-high performance concrete bridge piers with different fiber types and seismic joint materials. *Eng Struct.* 2025;330(2):119961. doi:10.1016/j.engstruct.2025.119961.
85. Segura Jr CL, Sattar S, Hariri-Ardebili MA. Quantifying material uncertainty in seismic evaluations of reinforced concrete bridge column structures. *ACI Struct J.* 2022;119(3):141–52. doi:10.14359/51734486.

86. Abuassi M, Bisharah M. Machine learning-based assessment of seismic performance in fiber-reinforced polymer (FRP) retrofitted bridges. *Asian J Civ Eng.* 2025;26(3):1–13. doi:10.1007/S42107-024-01217-3.
87. Yang S, He Y, Leng J. Enhanced shape memory metal-coordinated poly(aryl ether ketone)s with tunable gradient-deformation behaviors as well as self-healing and reprocessing abilities. *ACS Appl Mater Interfaces.* 2022;14(17):20032–41. doi:10.1021/acsami.2c01728.
88. Jan R, Lone MA. Investigating the effect of bridge pier material type and related parameters on local scour. *Int J Hydrol Sci Technol.* 2023;15(4):421–34. doi:10.1504/ijhst.2023.131185.
89. Liu G, Wang X, Chen J, Zhou Y, Zhao L, Wang Q, et al. Experimental study on seismic behavior of seismic damaged RC frame joints with T-shaped columns rehabilitated using hybrid fibers–modified reactive powder concrete. *J Struct Eng.* 2026;152(2):04025267. doi:10.1061/jsendh.steng-15285.
90. Benshams A, Hatami F, Saybani M. Probabilistic seismic assessment of innovative concrete bridge piers with Engineered Cementitious Composites (ECC) by different types of shape memory alloys (SMAs) bars. *Smart Mater Struct.* 2023;32(3):035039. doi:10.1088/1361-665X/acbcb0.
91. Qian J, Sun J, You X, Zhu X, Guo T, Dong Y. Seismic vulnerability analysis of a novel bridge with a shape memory alloy washer-based rocking pier. *Structures.* 2025;82:110541. doi:10.1016/j.istruc.2025.110541.
92. Tsiavos A, Oswald L. Rehabilitation of buildings using multi-performance materials: synergetic seismic and energy retrofitting of masonry buildings based on timber and flax-fiber-reinforced, cement-free concrete. *J Mater Sci Mater Eng.* 2025;20(1):113. doi:10.1186/s40712-025-00343-3.
93. Lu J, Li Z, Teng J. Seismic resilience assessment for reinforced concrete frame structural systems based on complex network considering repair paths. *Structures.* 2025;77(11):109072. doi:10.1016/j.istruc.2025.109072.
94. Zhao D, Zhang J, Wang F, Liang H. Experimental and theoretical analysis on seismic performance of reinforced recycled brick-concrete aggregate concrete columns. *Structures.* 2026;88(8):111906. doi:10.1016/j.istruc.2026.111906.
95. Chortis A, Gkountas C, Melidis L, Katakalos K. Seismic performance evaluation of 3D-printed concrete walls through numerical methods. *Buildings.* 2025;15(17):3205. doi:10.3390/buildings15173205.
96. Warsi SBF, Panda B, Biswas P. Design of earthquake-resistant 3D printed concrete wall based on ACI 318-19: analytical investigation and numerical modelling. *Structures.* 2025;78:109371. doi:10.1016/j.istruc.2025.109371.
97. Zhang X, Liu X, He M, Chen L, Zhao D. Strength optimization of transverse retrofitting device for seismic isolated bridge based on seismic repair cost ratio. *Eng Struct.* 2024;317(4):118645. doi:10.1016/j.engstruct.2024.118645.
98. Al-Hamad EG, Ragab AM, Elattar MM, Sadek DM. Experimental comparison of fibers and nanomaterials in compression test and cost of high strength concrete in Egypt. *Civ Environ Eng.* 2022;18(2):736–49. doi:10.2478/cee-2022-0068.
99. Özkan C, Ökten MS, Gençoğlu M, Sayin B. Seismic upgrading of infilled RC frames having low concrete strength using engineered composites under cyclic and axial loading. *Structures.* 2023;58(3):105586. doi:10.1016/j.istruc.2023.105586.