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Analysis on Bridge Collapse Incidents Caused by Earthquakes and Mitigation Strategies

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Abstract. In recent years, bridge collapses under the action of earthquakes occur frequently, resulting in huge personal and property losses, affecting traffic safety and economic development. Therefore, it is very important to study the causes and preventive measures of bridge collapse in earthquake. First of all, this paper analyzes the damage of the three main parts of the bridge structure: the superstructure, the substructure and the bearing under the earthquake. Then, the technology of using shape memory alloy (SMA) to enhance the seismic performance of bridge piers is discussed, and a new system to prevent displacement through concrete and steel cable limiter is introduced. Finally, the typical cases of bridge collapse, including the earthquake damage of Xiaoshan Bridge and Fukae Bridge, are analyzed, and the suggestions of seismic design and structural health monitoring (SHM) are put forward. The research results show that the impact of earthquake on the bridge is multifaceted, and the overall performance of the bridge structure must be enhanced by the synergistic action of various components. The research of this paper is of great significance to improve the seismic design and disaster reduction ability of bridge engineering.

Keywords: Bridge collapse; Earthquake; Seismic Design; Shape memory alloy; Structural health monitoring.

1. Introduction

With the growing global emphasis on sustainable development, the sustainable construction of bridge engineering has become a central task in the development of global infrastructure in the 21st century. As an integral part of modern transportation systems, the design, construction, and maintenance quality of bridges directly impact transportation safety and reliability, as well as the sustainable development of the socio-economic system. However, in recent years, bridge collapse incidents have frequently occurred, many during the construction and service phases, leading to significant loss of life and property damage. These incidents expose the challenges faced by bridge engineering in addressing sustainable development and intensify the pressures related to the five key factors: natural, resource, environmental, social, and economic sustainability [1]. Bridge collapse accidents not only endanger traffic safety but also exacerbate resource consumption and environmental pollution, disrupt social infrastructure, and impede economic operations. As a result, the prevention and resolution of bridge collapse accidents have become focal points of research for scholars, research institutions, and government departments.

In line with the concept of sustainable development, the causes of bridge collapse can be broadly classified into two categories: those occurring during the construction phase and those during the service phase. Construction-phase collapses are typically associated with unreasonable design, inadequate construction quality management, and human errors, whereas service-phase collapses often result from insufficient inspection, maintenance, and management, where hidden dangers are not addressed in a timely manner. Simultaneously, external natural factors, such as natural disasters and extreme weather conditions, pose significant threats to the structural stability of bridges. Studies have shown that natural disasters, particularly floods, earthquakes, heavy rainfall, and typhoons, are major natural factors leading to bridge collapses [2]. Many bridges fail during extreme weather conditions because their design did not adequately account for these natural disasters, or the disaster prevention measures were insufficient.

In addition, factors such as improper construction schemes, inadequate on-site management, and poor-quality control during construction are the primary human-related causes, particularly in the construction phase. In the service phase, overloading and vehicle collisions are key human-related factors contributing to bridge collapses. For instance, many bridges suffer structural damage due to frequent passage of heavy vehicles that exceed the design load capacity, ultimately leading to collapse. Additionally, some bridges experience structural fatigue, fractures, or failures after being impacted by collisions during traffic accidents. This paper analyzes the causes of bridge collapse incidents triggered by earthquakes as the primary natural factor and proposes corresponding preventive measures to provide scientific guidance for the sustainable development of bridge engineering.

2. Accident Analysis under Earthquake Causes

2.1. Design and Construction Issues

Earthquakes present particular challenges for the design and construction of bridges. The design must ensure sufficient seismic performance, including the use of appropriate safety factors, structural redundancy, and full consideration of geological conditions to guarantee the bridge’s stability during seismic events. During construction, strict quality control is necessary, with the use of standard-compliant materials and construction methods that accurately implement the design specifications. Moreover, effective communication and coordination between the design and construction teams are crucial to avoid misunderstandings that could undermine the bridge’s seismic resistance. Even after the design and construction phases are completed, regular inspections of the bridge’s seismic performance, as well as necessary maintenance and reinforcement, are required to maintain its earthquake resistance. These combined measures ensure that the bridge has sufficient safety and reliability when faced with seismic threats [3].

2.2. Overloading Issues

Overloading is a major cause of bridge collapses. When vehicle loads exceed the bridge's design capacity, it leads to structural damage or the accumulation of fatigue cracks, which can eventually result in bridge failure. In some cases, overloading may not have been considered during the design phase, making the bridge incapable of handling extra loads in actual usage. Additionally, a recent article from *Highways Today* pointed out that nearly half of bridge collapse incidents are related to overloading. Some heavy trucks carry loads exceeding 200% to 300% of their rated capacity, far beyond the bridge’s design load. Despite government measures such as fines to curb overloading, these efforts have not effectively resolved the issue. Overloading remains widespread, creating a vicious cycle where operators, driven by profit motives, continue overloading despite fines and bribes. Due to market competition pressures, many transportation companies choose overloading as a cost-cutting measure, which not only severely damages bridge structures but also increases the risk of bridge collapse during natural disasters such as earthquakes. Therefore, without effective control and management of overloading, regardless of the quality of bridge design and construction, the safety of bridges cannot be guaranteed [4].

2.3. Natural Disasters

Natural factors are a significant driver of bridge collapses, including earthquakes, floods, scour, landslides, debris flows, hurricanes, typhoons, tornadoes, and tsunamis. Earthquakes can cause structural damage to bridges, while floods and scour can destabilize the bridge foundation. Landslides and debris flows may alter the natural support conditions of bridges, and strong winds and tsunamis may directly lead to structural failure. These disasters highlight the necessity of considering the safety of bridges under extreme weather and seismic conditions during design and construction [5]. The article points out that earthquakes are a key natural factor in bridge collapses, as their suddenness and destructive force can severely impact bridge structural safety. During the Wenchuan earthquake, damage to bridges was particularly severe, with a total of 2,105 bridges damaged, underscoring the destructive impact of earthquakes on bridges. To address the threat of earthquakes, bridge design must incorporate sufficient safety factors and seismic measures, including selecting appropriate bridge types and using seismic isolation and energy dissipation technologies. Additionally, health monitoring and safety assessments of bridges are crucial for timely detection and repair of structural damage. For existing bridges, seismic retrofitting and modifications are effective means of improving their survivability during earthquakes. Although progress has been made in the study of the dynamic response of bridge structures, challenges remain in the theories and methods for identifying structural damage, necessitating further research to enhance the seismic performance of bridges.

3. Earthquake-Induced Accident Analysis

3.1. Xiaoshan Bridge

The collapse of Xiaoshan Bridge, located in Xiaoshan District, Hangzhou, Zhejiang Province, China, on April 14, 2017, resulted from a combination of factors (as show in Fig. 1). The bridge was originally designed as a symmetric box-girder structure, but the design was later altered to an asymmetric design, with a pedestrian walkway added to the west side, causing the bridge's center of gravity to shift. Deviations during construction, such as the misalignment of bearing pads from their designed positions, further reduced the bridge’s lateral stability. On April 12, 2017, a 4.2-magnitude earthquake caused the bridge's main structure to shift approximately 10 centimeters westward, leading to localized compressive damage to the bearing pads, which in turn created a sliding surface that ultimately resulted in the bridge's collapse. Additionally, certain bolts on the bridge had gradually deteriorated due to sustained horizontal forces, which may have accelerated the collapse. This case underscores the importance of cautious design, strict construction quality control, and regular inspection and maintenance of existing bridge [6].

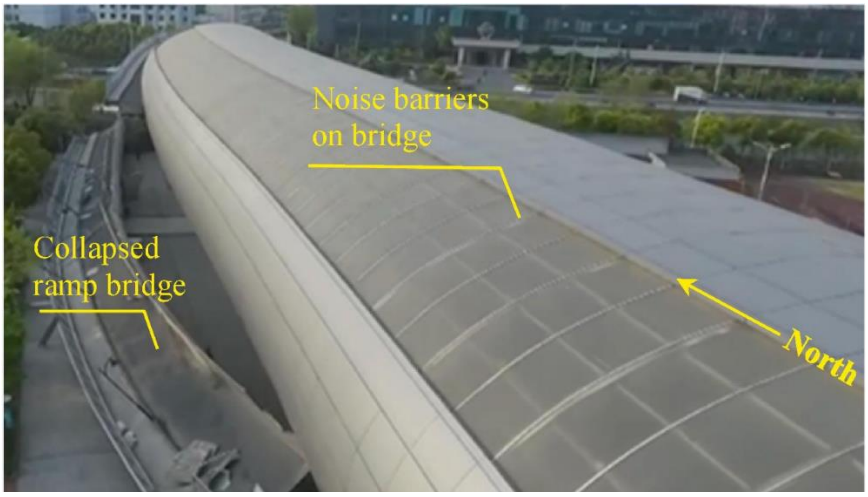
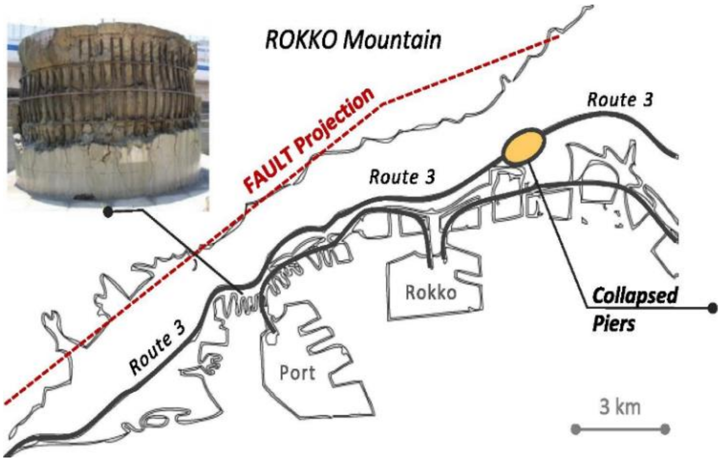


Figure 1. The collapse site of Xiaoshan Bridge [6]

3.2. Fukae Bridge

During the 1995 Kobe earthquake, the Fukae Bridge experienced a dramatic collapse, involving the failure of 18 spans of the elevated bridge and the 3.1-meter diameter piers integrally connected to it (as shown in Fig. 2). Although the piers were designed with sufficient strength, the shear force and bending moment induced by the earthquake exceeded the design expectations, leading to shear failure at a height of more than 2.5 meters above the longitudinal reinforcement cut-off points. The disaster was exacerbated by the absence of consideration for the "capacity design" concept and the negative effects of soil-foundation-structure interaction during the design phase. Finite element analysis revealed that, even with an overdesigned pile group, significant rocking would occur during the earthquake, causing alternating tension and compression within the pile group and a reduction in stiffness. This, in turn, led to load redistribution, preventing failure of the weaker piles. Nevertheless, the brittle failure mode of the piers and the severity of the earthquake ultimately caused the bridge to collapse. This event highlights the importance of considering soil-structure interaction in seismic engineering and reveals that even if the foundation structure appears intact after an earthquake, the failure of the superstructure can still lead to the collapse of the entire system [7].



(a) The Hansin expressway Route 3 in Kobe

(b) Post-seismic photo of the collapsed bridge

Figure 2. Kobe's dense infrastructure and photos of the fukae collapse [7]

4. Countermeasures

4.1. Bridge Structure and Seismic Resistance Methods

Under seismic activity, different parts of a bridge structure experience varying degrees of damage (as show in Fig. 3), providing essential insights for developing mitigation strategies. A bridge structure can be divided into three main components: the superstructure (which includes the bridge deck, main girders, and crossbeams), the substructure (which includes piers and abutments), and the bearings. In the superstructure, sliding and displacement are common, as the horizontal motion of an earthquake can cause relative sliding between the bridge deck and the bearings, sometimes leading to the deck dislodging [8]. In the substructure, the piers, which bear vertical loads, are particularly vulnerable to shear failure, crushing, cracking, and horizontal or vertical displacement of abutments during an earthquake [9]. The bearings, which connect the superstructure to the substructure, are susceptible to sliding, shear failure, or dislodgement due to horizontal movements, which can lead to bearing failure.

(a) The collpase of Gaoyuan bridge

(b) The damage of A2 abutment (c) The slippage of girders

(d) The damage of A1 abutment

Figure 3. The seismic damage of Gaoyuan bridge [10]

Over the past few decades, numerous methods have been proposed to enhance the seismic resistance of these bridge components. Ren et al. [11] highlighted that pier are the most vulnerable part of the structure, making them crucial for improving the overall seismic resistance of bridges, as show in Fig. 4. For example, Li et al. [12] proposed the use of Shape Memory Alloy (SMA) reinforcement in critical areas, such as the plastic hinge regions of piers, instead of conventional reinforcement (as show in Fig. 5). However, SMA has a lower elastic modulus than steel, which reduces the initial stiffness of SMA-Reinforced Concrete (RC) piers compared to conventional RC piers. To counterbalance this, a new bridge system combining SMA RC piers with SMA cable restrainers has been developed, providing enhanced stability during severe seismic events.

SMA, initially applied in aerospace engineering, has recently gained prominence in civil engineering due to its shape memory effect and superelasticity (as show in Fig. 6 and Fig. 7). These properties make SMA ideal for seismic retrofitting, as it dissipates energy through phase transitions in its crystal structure, displaying superelastic behavior during loading and unloading. Furthermore, the residual strain of SMA can be completely reversed through heating, showcasing its shape memory effect. This enables the material to introduce recovery stress into structures, facilitating prestressed reinforcement and fatigue strengthening. SMA composites can significantly enhance the flexural stiffness and bearing capacity of reinforced beams [13].

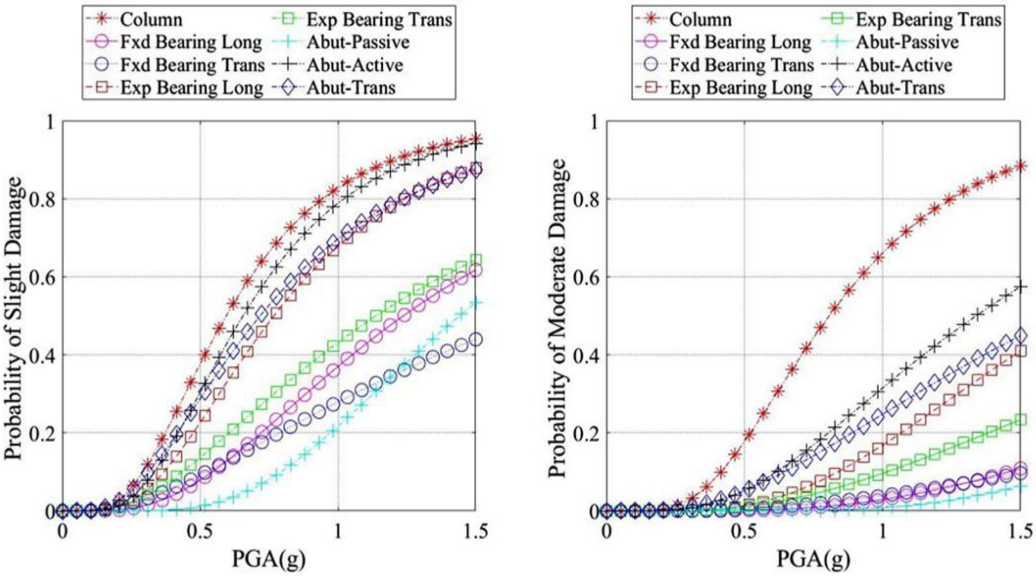


Figure 4. Seismic fragility of the bridge components [11]

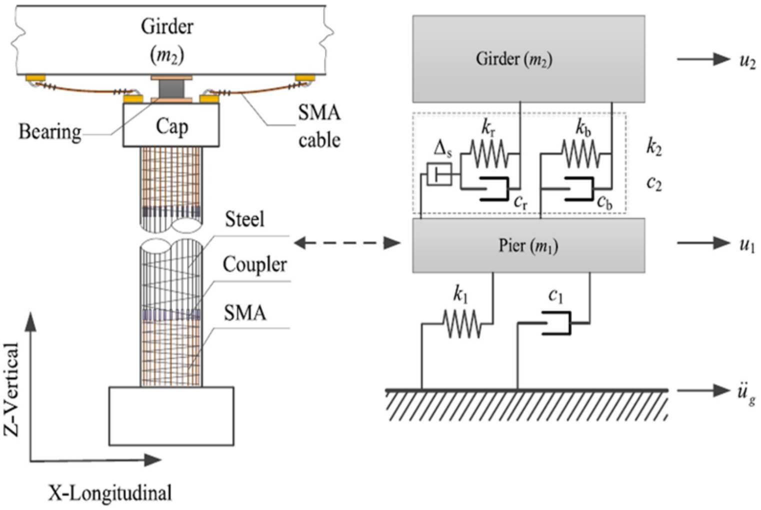


Figure 5. The proposed self-centering bridge system [12]

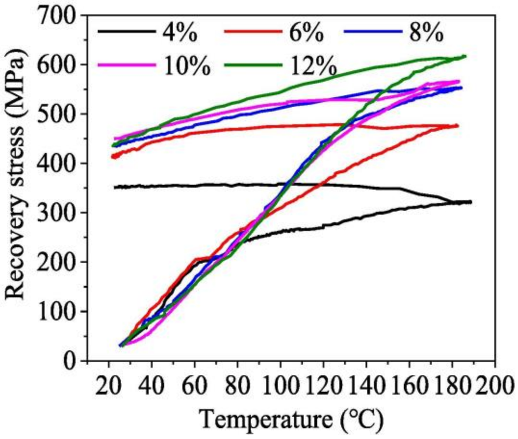


Figure 6. Recovery stress and temperature curves [13]

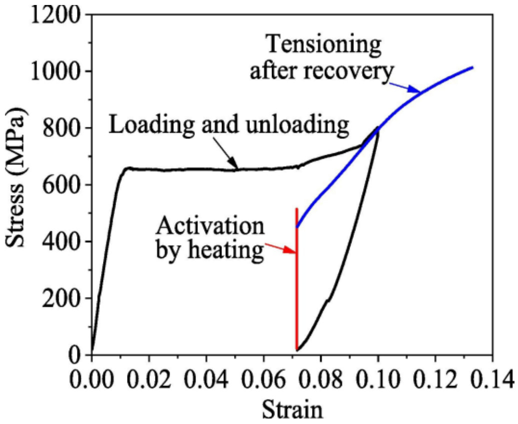
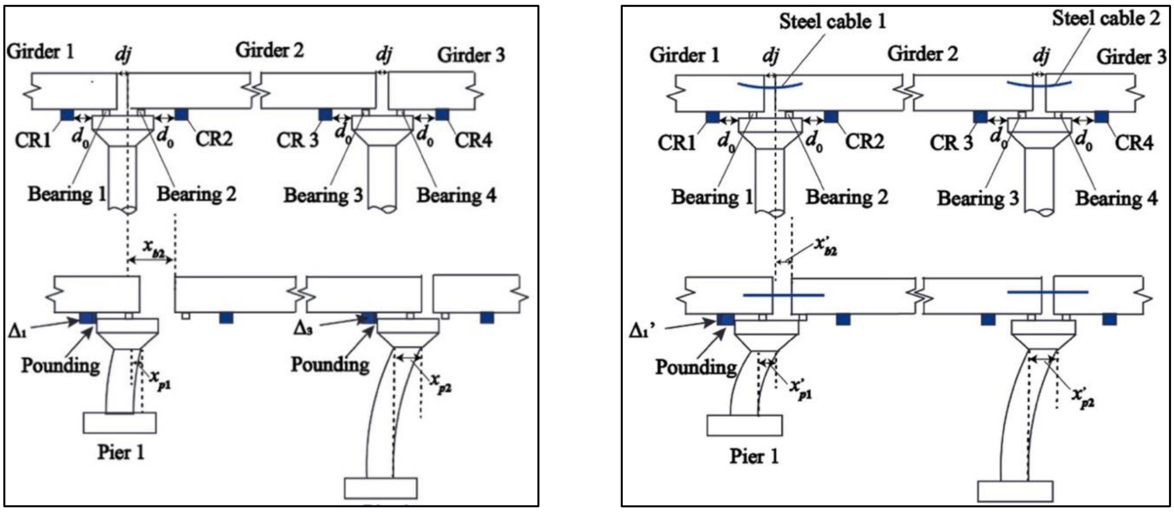


Figure 7. Stress and strain curves for the recovery and tensile processes [13]

While improving the seismic resistance of individual components is important, the overall stability of a bridge depends on the integrated performance of all its parts. To address this, Gao et al. [14] proposed a novel displacement prevention system involving concrete restrainers and steel cables between adjacent superstructures, which prevents longitudinal displacement of flexible transition piers in highway bridges (as show in Fig. 8). This system, combining concrete and cable restrainers, offers advantages such as stable performance, ease of construction, and market adoption, significantly improving the seismic resistance of the superstructure while maintaining balance with the substructure's stability.



(a) Concrete restrainer (b) Combined concrete and cable restrainers (CCCR)

Figure 8. Configuration of two unseating prevention restrainers [14]

4.2. Structural Health Monitoring (SHM)

With the continuous rise and development of network technology, seismic resistance and disaster mitigation in bridge engineering are no longer limited to material strength and structural design. Significant breakthroughs have been made in the realm of preventive measures. One promising direction is SHM, which leverages advancements in mobile technology. With the rapid development of smartphones, these devices show great potential in the field of bridge health monitoring (as show in Fig. 9). Equipped with built-in accelerometers, cameras, and other sensors, smartphones, when combined with computer vision and machine learning algorithms, can monitor vibrations, detect cracks, and assess environmental impacts on bridges in real-time [15].

This technology not only increases the frequency and scope of monitoring but also enhances data collection through crowdsourcing, involving more participants in the process. Despite challenges such as data accuracy and environmental interference, the portability and widespread availability of smartphones make them an indispensable tool for the future of bridge health monitoring. Smartphones are expected to play a pivotal role in predicting and preventing bridge failures, contributing to the overall safety and longevity of infrastructure. As technology continues to advance, it is anticipated that smartphones will become an even more integral part of health management not only for bridges but also for a wide range of other infrastructure systems.

This integration of mobile technology into SHM systems represents a significant shift towards more dynamic, decentralized, and scalable monitoring approaches. It opens up opportunities for real-time data collection at a lower cost compared to traditional monitoring methods, which often rely on stationary sensors and costly equipment. Additionally, the data gathered from smartphones can be analyzed using machine learning techniques to identify patterns and potential structural risks, leading to more timely interventions. Therefore, as these technologies mature, they hold the promise of improving infrastructure resilience and enhancing the sustainability of bridge maintenance practices.

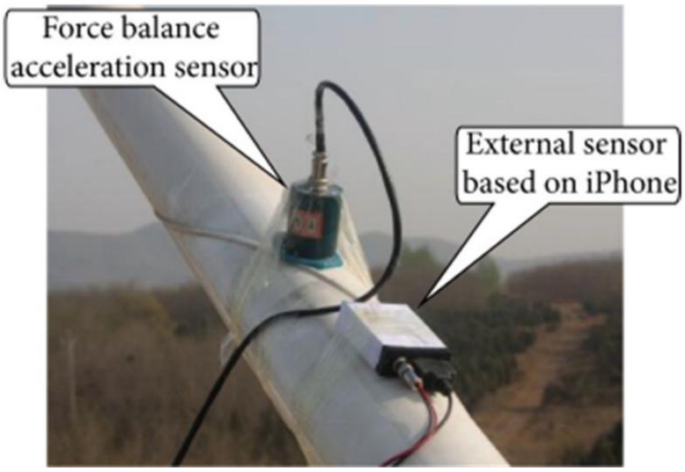


Figure 9. Sensor deployment on the bridge cable [15]

5. Conclusion

This paper provides a comprehensive examination of the multifaceted impacts of earthquakes on bridge collapses. Through the analysis of two specific case studies, Xiaoshan Bridge and Fukae Bridge, it becomes evident that seismic resistance and disaster mitigation for bridges require consideration of numerous factors related to design, construction, and material selection. The severe impact of earthquakes on bridges manifests in various ways, influencing structural integrity, functionality, and long-term resilience. Therefore, when formulating corresponding countermeasures, a more holistic approach must be adopted, integrating not only traditional engineering principles but also modern advancements in technology.

The lessons drawn from these case studies underscore the complexity of seismic influences on bridge structures. Earthquake-induced damages are not isolated to a single aspect of the structure but are rather a result of compounded effects on the foundations, superstructure, and materials used. Thus, addressing these challenges requires continuous improvement in both design and construction methods. Simultaneously, keeping pace with technological advancements, such as leveraging the internet and other innovative fields, can significantly enhance earthquake preparedness and bridge safety. The integration of these new technologies offers promising directions for the future, providing engineers and planners with more precise tools for monitoring, analyzing, and preventing potential damages caused by seismic events.

Furthermore, this approach can elevate the discipline of earthquake engineering, contributing to more robust and resilient infrastructure. The utilization of real-time data, simulation models, and predictive analytics through digital platforms enables more effective decision-making and maintenance strategies. These advancements not only improve immediate disaster response but also support long-term sustainability in bridge construction and maintenance practices. In addition to these seismic considerations, the findings from these case studies also offer valuable insights into broader bridge engineering practices. The integration of cutting-edge technologies in seismic monitoring and response can inform future construction efforts, ensuring that bridges are designed and maintained to withstand the ever-evolving challenges posed by natural disasters.

However, there are still many technical challenges and areas for improvement. For instance, the bridge models used are not yet fully developed and mature, and there remains room for optimization. The suitability of SMA materials is also in question—whether better materials might replace them in the future. The most significant challenge lies in overcoming technical barriers, as continuous technological advancements are needed to better respond to the impact of earthquakes. These issues require further research and resolution.

The fight against earthquakes continues to drive the evolution and optimization of bridge structures, enhancing safety. This is the direction toward which many bridge engineers are continually striving. While some aspects may not yet be perfect, these challenges also serve as motivation for learning about bridge engineering. in the future, better measures will be developed to benefit humanity.

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