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State of Art: Seismic Failure Impact on Concrete Bridges

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Abstract

Seismic failures in concrete bridges can lead to severe structural damage, resulting in partial or complete collapse, significant economic losses, and potential disruptions to transportation networks. Such failures may arise from inadequate design, aging materials, or insufficient seismic detailing, making bridges vulnerable during earthquakes. The impact includes immediate structural damage and long-term consequences for public safety and infrastructure resilience, highlighting the need for effective seismic-resistant designs and retrofitting strategies to minimize risks.

Introduction

The wrecking of bridges in big earthquakes like the Chi-Chi, Kobe, and Northridge quakes shows a real need for better ways to protect these structures from earthquake damage. For decades, retrofit plans have been used to prevent collapses caused by support loss. After the 1971 San Fernando earthquake, restrainer cables and bars were placed all over the U.S. to limit movement at the bridge joints. However, despite recent earthquakes proving that these restraints can work, many bridges with them still got seriously damaged or completely fell apart. Bridges with these cables failed during the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe quakes. Most of these failures were at connection points or due to punching shear in the concrete. These traditional restraints don't absorb much energy because they're made to stay flexible during earthquakes.

Studies show that you need a lot of stuff to keep joints in check, especially when big earthquakes hit. But if you go overboard, it can put too much pressure on other parts of the bridge. The old-school stuff can have issues, but using shape memory alloy (SMA) can help. They can act as both restrainers and dampers when they're super springy. SMAs can handle a lot of energy without wearing out and can stretch 6–8%. This means they can take care of a lot of energy for their size, making everything work better.

Grasser and Cozzarelli assessed the effectiveness of Nitinol SMAs as seismic dampers, investigating how loading frequency and historical context influence energy dissipation in Nitinol wires. They also created a model to describe pseudo-elastic behavior, which they subsequently verified through experimental methods.Inaudi and Kelly studied SMA wires in steel frame models with tuned mass dampers, finding improved earthquake performance by matching prestress tension with the structure's natural frequency. Although the effects vary, Sweeney, Hayes, and Clark noted that SMA wires reduces accelerations and displacements.

In Japan, Wilde's team examined an SMA device in a bridge base isolation system, which effectively limited movements and absorbed earthquake energy. Adachi and Unjoh's scaled-down experiment concluded that SMAs perform better in the martensitic phase than the austenitic phase.

Few full-scale tests of SMA devices for bridges have been conducted despite many studies on smaller models. This study tests an SMA restrainer bar of 25.4 mm under cyclical tension loads and develops an analytical model to evaluate its performance in multi-span supported bridges. While the findings provide valuable insights, the research is limited in scope.[1].

Literature Review

R. DesRoches and M. Delemont pointed out that recent earthquakes in the U.S. and Japan have revealed that bridges tend to collapse at hinges and ends. This research investigates using SMA restrainer bars to make bridges safer during earthquakes. By testing 25.4 mm diameter SMA bars with cyclical strains of up to 8%, minimal damage was found. The study of a typical multi-span supported bridge showed that SMA restrainer bars greatly reduce movement at piers and ends, which is helpful during intense ground shaking [1].

Through inventory analysis, Eunsoo Choi, Reginald DesRoches, and colleagues developed fragility curves for common bridge types in the Central and Southeastern United States (CSUS). They identified four typical bridge types and used nonlinear models with synthetic ground motions to create analytical fragility curves. Their research indicates that the peak ground acceleration for a 50% chance of slight damage ranges from 0.19 to 0.24 g. The most vulnerable types are multi-span supported and multi-span continuous steel-girder bridges, while the multi-span continuous prestressed concrete-girder bridge is the least vulnerable. These curves aid in estimating economic losses and prioritizing retrofitting efforts, particularly as seismic retrofitting becomes increasingly necessary in the region [2].

Zhenyu Zhu, Iftekhar Ahmad, and their team explored concrete-filled fiber-reinforced polymer (FRP) tubes (CFFT) as a faster, stronger alternative to traditional reinforced concrete (RC). Their study validates traditional analytical methods for predicting CFFT structural performance during earthquakes, comparing CFFT columns—cast-in-place or precast with RC foundations—to RC columns. They conducted a parametric study under constant axial and reversed cyclic loads, using three ground acceleration records. Results indicated that CFFT columns often outperformed RC columns and that optimizing the FRP tube's fiber design could enhance strength and flexibility. Sufficient internal steel reinforcement and a minimum FRP tube thickness are essential to ensure seismic integrity [3].

Bryant G. Nielson and Reginald DesRoches note that steel girder bridges are prevalent in the Central and Southeastern U.S. With rising earthquake awareness, engineers must understand their behavior during seismic events. A new study on a steel bridge with multiple spans found major weaknesses in the concrete columns and steel bearings when a detailed 3D model was used. It found that longitudinal loading exerts more strain than transverse loading, although both can cause significant damage. Key factors affecting earthquake response include load direction, damping ratio, and stiffness of fixed bearings, all essential for assessing seismic risks [4].

Yael Van Den Einde, Vistasp M. Karbhari, and others studied FRP composites for cable-stayed bridges, particularly in seismic areas. Their research, based on full-scale tests, examined the tensile performance of splice connections. The findings showed that these connections could withstand more force than a bridge would encounter, with earthquake resistance nearly six times greater than required, and the strain in the composite shell remained within safe limits [5].

Reducing the impact of earthquakes on people and property is crucial. In the last century, advancements in earthquake science and engineering have decreased the number of earthquake deaths threefold. However, growing populations have led to increased deaths and costs. This chapter explores global seismic hazards and strategies to minimize damage. While many believe predicting earthquakes is the solution, focusing on building earthquake-resistant structures is more practical. Design improvements are based on past performance, and new simulation methods help assess future buildings' resilience. The priority is to prevent deaths and economic losses, with rapid response systems providing quick seismic data. Dense sensor networks aim to offer early warnings, helping to mitigate the impacts of earthquakes worldwide [6].

Chang Su Shim, Chul-Hun Chung, and others highlight the growing demand for faster bridge construction due to stringent safety standards and traffic management needs. They propose prefabricated bridge piers to expedite the process and examine precast piers using bonded prestressing bars and steel tubes. The study focuses on the seismic performance of seven precast pier samples, assessing variables like prestressing bars, prestressing force, and joint placement. Results show that axial prestress reduces deformation from minor side movements but fails to aid self-centering during significant damage. Joint design where the pier attaches to the foundation is crucial for controlling cracks, with recommended transverse reinforcement matching standard RC piers for ductility. Additionally, increasing steel content enhances plastic deformation and energy absorption, while the number of joints affects energy absorption capacity [7].

Samer El-Bahey and Michel Bruneau discuss the concept of structural fuses, which involves adding flexible, easy-to-replace steel parts to RC bridge supports to enhance strength and stiffness. These additions help absorb seismic forces through hysteretic behavior, keeping RC bridge piers elastic. This approach benefits new and existing bridges, particularly for retrofitting older, inflexible supports. The paper emphasizes using Buckling Restrained Braces (BRBs) as structural fuses and provides a formula for design parameters validated through nonlinear time history analyses. The proposed method indicates that BRBs can significantly improve seismic performance, with a visual approach to find acceptable design solutions that become more limited as frame strength increases, necessitating larger fuses for effectiveness [8].

A. Khaled, R. Tremblay, and others investigated the 30% rule effectiveness the in the prediction process of bridge columns seismic demand during earthquakes in Montreal and Vancouver. Using real and simulated earthquake data, they analyzed generic bridge models to assess column responses to different earthquake forces. Their findings indicate that the 30% rule offers a reliable estimate of the elastic seismic demand on bridge columns, though its effectiveness varies with ground motion types and bridge designs [9].

This paper outlines a method to assess risk and enhance the design of supplemental dampers in multi-span bridges with isolation bearings. It includes a bridge model that accounts for the isolators and dampers nonlinear behavior, dynamic abutment response, and pounding effects. A nonlinear dynamic analysis evaluates performance, while realistic ground motion models link to site-specific seismic risks. A probabilistic approach incorporates uncertainties in structures and excitations, facilitating understanding seismic risk through selected probability models. Stochastic simulation calculates expected values and optimizes damper features. A probabilistic sensitivity analysis identifies the most influential uncertain parameters, and an example demonstrates the nonlinear viscous dampers design for a two-span bridge [10].

This study by Peyman Kaviani and Farzin Zareian investigates the RC bridges behavior with skewed seat-type abutments during earthquakes. Focusing on three short bridges in California, the researchers employed detailed modeling to analyze varying structural features, such as abutment skew angle and column height. Extensive nonlinear time-history analyses revealed that skewed abutments resulted in greater deck rotation and column drift than straight bridges. The findings show that larger abutment skew angles increase the risk of collapse due to excessive rotations, but using shear keys can significantly reduce this risk. [11].

A.H.M. Muntasir Billah et al. identify that structural steel rusting has led to building failures. At the same time, FRP bars offer corrosion resistance but are brittle, risking sudden failures. SMA can bend and return to their original shape when stress is removed, making them valuable for earthquake recovery. This study presents a hybrid design for RC columns that enhance corrosion resistance and reduce permanent damage by using SMA or stainless steel in the plastic hinge area and FRP or stainless-steel rebar elsewhere. The performance of these hybrid columns was evaluated under earthquake conditions. It showed a significant reduction in residual displacement while effectively dissipating energy compared to similar RC columns reinforced with stainless steel [12].

Gustavo H. Siqueira and Danusa H. Tavares studied Quebec's multi-span bridges, over 46% of which are concrete girders, and many are vulnerable to earthquakes. To enhance the resilience of these bridges, researchers developed a program to assess natural rubber seismic isolators usage. This paper analyzes how multi-span supported (MSSS) and multi-span continuous (MSC) concrete bridges perform in their original state and after retrofitting. It utilizes detailed 3D models and synthetic ground motions specific to eastern Canada. Key findings revealed that factors such as the stiffness of isolators and abutments, the gap between the bridge deck and abutment, bridge design, and ground motion characteristics significantly impacted performance. The study concluded that while seismic isolation devices lessen column bending demands, they increase deformation demands on abutment walls [13].

Yuye Zhang and D. Dias-da-Costa investigate the earthquake resilience of multi-span continuous girder (MSCG) bridges, emphasizing the role of columns. The study examines columns made from RC, steel FRC (SFRC), and a mix of both. Eight columns were tested for load capacity to validate computer models. Simulations predicted MSCG bridge performance during earthquakes, leading to fragility curves that assess damage likelihood based on ground shaking intensity. Key findings include SFRC columns with a 1.0% fiber ratio providing more cost-effective strengthening than those with 1.5%. MSCG bridges with SFRC or RC-SFRC columns are less vulnerable to stronger earthquakes than those with only RC columns. SFRC, used only at plastic hinges, offers similar earthquake resilience as fully SFRC columns. These insights suggest effective retrofitting strategies for MSCG bridges in earthquake-prone regions [14].

A.H.M. Muntasir Billah et al. investigated using SMA as an alternative to traditional steel reinforcement in bridges to enhance their earthquake resistance. They examined concrete bridge piers reinforced with various SMAs, including Ni-Ti, Cu-Al-Mn, and Fe-based alloys, and assessed seismic risk and performance goals. The researchers created seismic demand models, focusing on maximum and residual drift, and developed fragility curves for the bridge piers. Their findings indicated that all piers met design goals, with varying performance based on the SMA type. Notably, the FeNCATB-SMA (SMA-3) reinforced pier outperformed the others, demonstrating a low chance of collapse during severe earthquakes [15].

Xiaowei Wang, Jiaxin Fang, and colleagues investigated the damage to RC pylons in cable-stayed bridges during the 1999 Chi-Chi earthquake. Their study used model tests and computer simulations to analyze pylon failure and flexibility under earthquake conditions. They applied a two-point load pattern at the junction and crossbeam, correlating movement ratios with ground motion, particularly the bracketed duration, ultimately choosing a movement ratio 5.0 for tests. Results indicated that tower failure occurs flexibly, with sequential plastic hinges forming, starting at the bottom of the upper column and then at both ends of the lower column. They identified several displacement ductility factors based on the number of plastic hinges. The computer model also showed that lower movement ratios shifted the first hinge formation from the upper to the lower column [16].

Menghan Hu, Qiang Han, and others researched multi-scale finite element (FE) modeling to balance speed and accuracy in engineering. They focused on the damage to the Gaoyuan Bridge during the Wenchuan earthquake, developing a method in LS-DYNA to connect solid and beam elements. Their findings indicated that the A2 abutment's failure, coupled with strong forces, caused the loss of support for the bridge's superstructure, leading to the fall of rafters in the third and fourth spans. This multi-scale FE modeling effectively simulated local damage and potential collapse during strong earthquakes, closely matching the observed damage of the Gaoyuan Highway Bridge [17].

Scouring significantly contributes to bridge failures, so understanding its effects on pile foundations for bridge safety is crucial. This study examines scouring around the Boğaçay Bridge in Antalya, Turkey, through models simulating soil-structure interactions. Researchers analyzed how increasing scour depths, up to six meters, impacted the bridge, particularly seismic activity per the Turkish Earthquake Code. The findings revealed that greater scour depths increased the bridge's natural periods and displacement demands on the piers, shifting plastic hinges from the piers to the piles. This shift decreased the internal forces in the pier columns and led to higher bending moments and

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rotations in the piles. The findings really stress how crucial it is to consider the possibility of erosion and earthquakes when designing bridge foundations., especially for river-crossing structures [18].

V. Ozsarac, M. Furinghetti, and colleagues highlight the need to understand aging bridge components better when evaluating seismic risk. These components mechanical properties can change over time, and varying modeling methods in the literature can greatly impact measures like mean annual frequency of collapse (MAFC) and the expected annual losses (EAL). This study focuses on bridge bearings, particularly unreinforced thin elastomeric pads common in Italian bridges from the 1960s and '70s. Using Latin Hypercube Sampling, researchers analyze parameters like shear modulus and the friction coefficient between rubber and concrete. The results indicate that while changes in shear modulus have minimal impact, variations in the friction coefficient can significantly affect risk measures [19].

Evaluating the seismic risk of older bridges is challenging due to limited knowledge of their key components and changing mechanical properties over time. Different recommendations can lead to varying modeling parameters, significantly impacting bridge responses to seismic events and influencing risk measures such as EAL and MAFC. This study examines the effects of often-unknown features of bridge bearings using unreinforced thin elastomeric pads, which were common in Italian bridges from the 1960s and 1970s. We performed a case study on a specific bridge using Latin Hypercube Sampling to analyze variations in friction coefficient between rubber and concrete surfaces and shear modulus. Our findings indicate that while changes in shear modulus have a minor effect, variations in friction greatly influence risk metrics [20].

Si-Qi Li, Ke Du, and others examined how varying levels of earthquake strength impact damage to RC buildings. Their study analyzed 1,472,379 acceleration records from the 2008 Wenchuan earthquake to understand how directional ground motion affects floor damage. They also looked at damage during the Mw6.2 Jishishan earthquake in Gansu Province on December 18, 2023. The researchers modeled a four-story RC frame structure in 3D and simulated seismic shocks from different directions (0°, 30°, 60°, and 90°) using finite element methods. They developed damage assessment curves and stress distributions for 1- to 4-story RC structures, finding that in intensity zone IX, seismic activity from the 0° direction most significantly affected the first floor, aligning with field observations [21].

Conclusions

1. This study examines the seismic risk performance of existing RC bridges, emphasizing the importance of measuring the flexural and split tensile strengths due to plain concrete's brittleness. [19].
2. It analyzes the damage and vulnerability of RC frame structures during earthquakes, highlighting typical damage characteristics and failure modes [20].

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