A Review of the Research on the Failure Behaviors of Bridge Structures under Impact Loads

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Abstract: Bridge structures are essential facilities for public production and daily life, and the consequences of their failure under different impact loads have focus of research in the field. This paper reviews research advancements in China regarding bridge structures under impact loads, first highlighting the critical role of bridges in connecting regions and supporting socioeconomic activities and the vulnerability to diverse loads. Based on literatures research, this study systematically synthesizes failure behaviors under single loads (including wind, waves, explosions, rockfalls, and vehicles) and coupled multi-loads (such as seismic-debris flow, wind-vehicle, wave-seismic, and explosive-seismic), conducting in-depth analysis of their respective action mechanisms. The conclusions indicate that current research predominantly focuses on single impact loads, while there is insufficient understanding of multi-load coupling mechanisms, especially complex interdisciplinary interactions involving multiple physical fields. Therefore, future studies should emphasize exploring multi-field effects of coupled loads to optimize bridge structural designs and effectively enhance their disaster resistance capabilities.

Keywords: Bridge Structure; Impact Load; Single Load; Multi Load Coupling

1. Introduction

Road and bridge structures play an irreplaceable role in ensuring public transportation, daily life, and safety, serving as the lifelines that connect cities, rural areas, and industrial hubs. Their seamless operation underpins economic activities, enabling the efficient movement of goods and people, and ensuring access to essential services even in remote regions. However, their structural integrity is frequently challenged by a variety of external loads, each with unique characteristics and destructive potentials. Natural disasters like sudden floods, which not only erode foundations but also exert lateral pressures that can shift bridge piers off their bearings, traffic-induced forces such as overloaded vehicles—often exceeding weight limits by 50% or more—that exert excessive pressure on deck systems and accelerate fatigue in steel girders, and human-related accidents like improper construction operations, such as unauthorized cutting of structural members or inadequate welding during maintenance, all highlight their vulnerability to catastrophic failures. A notable example is the collapse of the bridge on the Danning Expressway in Shaanxi Province in 2024, which resulted in 38 fatalities and 24 people missing—underscoring the accidental nature and high destructiveness of bridge accidents [1]. Post-incident investigations revealed that a combination of heavy rainfall-induced foundation erosion and long-term overloaded truck traffic had weakened the structure over time, culminating in a sudden failure during peak hours. Beyond such major incidents, minor damages accumulating over time due to repeated load impacts can also lead to gradual structural degradation, posing hidden risks. For instance, micro-cracks in concrete decks caused by repeated vehicle vibrations can expand under freeze-thaw cycles, allowing water infiltration that corrodes reinforcing steel and compromises the entire structure's integrity.

Consequently, research on the seismic resilience and disaster resistance of bridge structures remains a critical scientific and engineering issue that demands resolution in contemporary times. With climate change intensifying the frequency and severity of extreme weather events, and urbanization increasing traffic volumes, the need for robust analytical frameworks and innovative protective technologies has never been more pressing. Against this backdrop, this paper systematically synthesizes and discusses the research advancements in China pertaining to impact loads on road and bridge structures, covering aspects from load mechanism analysis—such as quantifying the dynamic response of bridges under combined wind and vehicle loads—to protective measure development, including the application of high-performance materials like fiber-reinforced polymers and smart monitoring systems that detect early signs of structural distress. By integrating theoretical studies, numerical simulations, and field test data, this review aims to provide new insights and references for researchers in the field of road and bridge engineering, fostering the development of more resilient infrastructure that can withstand the multifaceted challenges of the 21st century.

2. Overview of Bridge Load Research

The interaction between road and bridge structures and various types of loads is highly complex, and assessing their performance under the combined action of extreme loads and operational loads remains particularly challenging. Extreme loads, such as sudden earthquakes with unpredictable magnitudes and durations, often strike in tandem with long-term operational loads like constant vehicle vibrations and cumulative wind erosion, creating a dynamic interplay that defies simple modeling. As an interdisciplinary problem involving geological conditions—such as soil stiffness and foundation stability—climatic factors including seasonal temperature fluctuations and precipitation intensity, and human-induced configurations like irregular maintenance or unapproved structural modifications, it still lacks a comprehensive solution. Current analytical frameworks frequently isolate individual load factors, failing to capture the synergistic effects that can amplify structural stress by up to 30% in some cases, as observed in recent case studies. The causes and evolutionary characteristics of multi-load factors—such as earthquakes and debris flows—exhibit significant variability. Earthquakes transmit energy through ground motions that vary with geological strata, while debris flows combine hydrodynamic forces with abrasive impacts from entrained boulders, each imposing distinct failure modes on bridge piers and decking. To address this, this study reframes the issue as an investigation into the impact load effects on bridge structures, integrating data from real-world disaster assessments and laboratory simulations. By examining the failure behaviors of bridge structures under single or coupled multi-load effects—ranging from fatigue cracks under cyclic vehicle loads to abrupt shear failures during seismic-wave propagation—this research aims to develop predictive models that account for load sequence and intensity. Ultimately, such insights will provide effective support for advancing the seismic and disaster-resistant capabilities of bridge systems, guiding the design of adaptive structures that can mitigate risks across diverse environmental and operational scenarios.

3. Research on Failure Behaviors under Single Load

3.1 Wind Loads

Wind loads exert multifaceted effects on bridge structures, primarily influencing their stability through static wind forces, fluctuating wind forces, and self-excited forces [2]. Static wind force refers to the force generated by steady winds acting on the bridge, which is related to factors such as the bridge's windward area, wind speed, and wind load shape coefficient. When static wind force exceeds the load-bearing capacity of the bridge structure, it can lead to structural deformation or even failure. Fluctuating wind forces, induced by the turbulent nature of wind, manifest as random vibrations in the bridge structure. The magnitude and frequency of these fluctuating forces are closely linked to wind speed, turbulence intensity, and the natural vibration characteristics of the bridge. Self-excited forces arise from the interaction between the wind and the bridge structure as the latter vibrates under wind action. When the frequency of self-excited forces approaches the natural frequency of the bridge, resonance may occur. Bridges with low torsional stiffness are unable to effectively resist the torsional forces generated by wind-induced vibrations, thereby resulting in structural failure.

3.2 Wave Loads

The damage to bridge structures caused by wave loads is primarily exerted through two mechanisms: hydrodynamic pressure and impacts from floating debris [3]. Hydrodynamic pressure constitutes one of the main loads imposed on bridge structures by floodwaters, with its magnitude closely related to factors such as flood flow velocity, discharge volume, and the shape and dimensions of the bridge structure.

Based on fluid mechanics principles, hydrodynamic pressure can be calculated using the Bernoulli equation. During flood events, the hydrodynamic pressure exerted by flowing water on piers and abutments may subject the bridge structure to enormous thrust forces, potentially exceeding its load-bearing capacity. Impacts from floating debris represent another critical factor contributing to flood-induced damage to bridges. Driven by high-velocity currents, floating debris accumulates significant kinetic energy, generating instantaneous impact forces upon collision with the bridge structure. The magnitude of such impact forces depends on factors including the mass and velocity of the debris, as well as the angle of impact. Furthermore, the action of flood loads is a dynamically evolving process, in which hydrodynamic pressure and debris impacts interact and influence each other. In the early stages of a flood, hydrodynamic pressure may be the primary driver of structural damage; however, as the flood intensifies, the contribution of floating debris impacts gradually increases.

3.3 Explosive Loads

Vehicle fuel explosions represent a fluid dynamic phenomenon. When bridge structures are subjected to explosive loads from vehicles, their stress and strain distributions exhibit complex characteristics, leading to various failure modes [4]. The structural surface of the bridge is subjected to instantaneous high pressure from the explosive load, resulting in a rapid surge in surface stress. Due to the extremely short duration of the explosive shockwave, the bridge structure does not have sufficient time to undergo significant deformation, causing stress to concentrate primarily on the surface and localized regions of the structure. Under the action of the explosive shockwave, stress concentration in the bridge structure becomes pronounced, with stress values at the base of piers and the joints between girders and piers far exceeding the yield strength of the material. As the shockwave propagates, stress within the structure undergoes further changes, potentially giving rise to phenomena such as stress concentration and stress wave reflection. These complex stress states impose enormous loads on the material of the bridge structure; when the stress exceeds the ultimate strength of the material, structural failure occurs, triggering overall instability of the bridge.

3.4 Rockfall Loads

Existing research primarily focuses on the impact of rockfall-induced forces—including their magnitude, duration, and point of application—on the local damage and overall stability of bridge structures [5]. As rockfalls descend from elevated positions, their velocity and potential energy gradually increase. In areas with highly undulating slopes, rockfalls may exhibit alternating motion patterns such as bouncing, rolling, and sliding. The duration of rockfall loading also varies significantly, depending not only on the rock's own motion characteristics but also on factors such as slope material and gradient. Short, intense impacts and relatively prolonged yet less forceful impacts induce distinctly different damage modes in bridge structures. Furthermore, localized damage characteristics differ markedly when rockfalls act on distinct components of a bridge, such as girders, piers, or abutments.

3.5 Vehicle Loads

Vehicle loads primarily encompass the vehicle's own weight, dynamic loads generated during driving, and impact forces induced by braking and acceleration. These loads exhibit distinct dynamic characteristics: road surface irregularities cause wheels to vibrate vertically, and such vibrations are transmitted to the bridge structure via tires, subjecting the structure to time-varying dynamic loads. Vehicle vibrations can be categorized into vertical, horizontal, and torsional modes. Vertical vibration, the most prominent form during vehicle movement, results in fluctuations in the vertical force exerted by the vehicle on the bridge. Horizontal and torsional vibrations, by contrast, introduce lateral and torsional forces, affecting the bridge's lateral stability and torsional resistance. The dynamic behavior of vehicle loads is also closely linked to factors such as vehicle speed, bridge span, and structural stiffness [6]. Higher driving speeds amplify the dynamic loads imposed on the bridge, while longer spans and lower stiffness enhance the structural dynamic response to vehicle loads.

4. Research on Failure Behaviors under Coupled Multi-Loads

Numerous safety accident investigation reports on road and bridge structures indicate that the study of bridge structural failure behaviors essentially stems from the consequences of coupled multi-load actions. For example, the collapse of some highway bridges in mountainous areas is often the result of the combined effect of heavy rainfall-induced debris flows and long-term vehicle overloading, where the debris flow erodes the bridge foundation and the overloaded vehicles weaken the main structure, leading to eventual failure. In response, scholars have conducted extensive and in-depth research on the impact of coupled actions involving earthquakes, debris flows, and other types of loads on bridge failure behaviors. They have employed various research methods such as numerical simulations, laboratory tests, and field investigations to analyze the mechanical response characteristics and failure mechanisms of bridge structures under different coupled load combinations. These studies aim to reveal the internal laws of bridge failure under coupled multi-loads, thereby providing effective theoretical support and technical solutions for bridge structural design, which can help engineers optimize structural parameters and improve the overall safety and durability of bridges.

4.1 Seismic Loads

Seismic waves generally consist of two primary types: longitudinal waves (referred to as P-waves) and transverse waves (referred to as S-waves). P-waves propagate at a relatively high speed and, when acting on the ground, induce vertical vibrations. In contrast, S-waves travel at a slower velocity. Additionally, the mixed waves (surface waves) generated by the interaction of P-waves and S-waves at the ground surface propagate the slowest but carry the most energy, exerting the most destructive effects on ground structures. Under the action of seismic waves, bridge structures are subjected to various forces, including inertial forces, damping forces, and elastic restoring forces. The magnitude and direction of these forces change continuously over time, causing the bridge to vibrate. The vibration response of the bridge structure is closely related to factors such as the characteristics of the seismic waves, the structural form of the bridge, material properties, and site conditions. Resonance occurs when the natural vibration frequency of the bridge approximates the frequency of the seismic waves, leading to a sharp increase in vibration amplitude and subsequent structural failure [7].

4.2 Debris Flow Loads

As a highly destructive natural geological hazard, debris flow impact manifests as a time-varying, sustained dynamic impact load, characterized by a wide damage range and long duration. Its impact process involves bidirectional coupling between fluid and solid phases. To simplify research, scholars have divided debris flows into two components—boulder impacts and debris slurry impacts—and conducted systematic studies. Specifically, research focuses on aspects such as the cross-sectional shape, alignment, strength, and stability of bridge piers; the tensile and compressive strength of piers; boulder impact velocity and impact force magnitude; and the damage effects caused by the particle size distribution of solid components in debris flows [8].

4.3 Wind-Vehicle Loads

Long-span bridge structures exhibit high sensitivity to the coupled dynamic responses induced by vehicles traveling on the bridge and wind loads. Studies have revealed that bridge vibrations caused by the combined action of vehicles and wind are predominantly vertical. At high wind speeds, bridge vibrations exert a more significant influence on vehicle responses, whereas at low wind speeds, road surface roughness becomes the dominant factor affecting vehicle behavior [9]. Furthermore, the dynamic responses of the bridge system increase with rising wind speeds, traffic density, and vehicle speeds. Notably, there exists a strong correlation between the speed limits for vehicles traveling on the bridge structure and wind speed.

4.4 Wave-Seismic Loads

The dynamic response of deep-water bridge structures under the combined action of earthquakes and waves is not equivalent to the superposition of their individual dynamic responses to earthquakes and waves [10]. Notably, the vibrations induced by wave action on bridge structures are predominantly lateral. Wave action exerts significantly different effects on the seismic dynamic responses of non-isolated and isolated bridge structures: isolated bridges exhibit smaller dynamic responses under the coupled action of waves and earthquakes. Therefore, investigations into the failure behaviors of bridge structures subjected to coupled wave-seismic loads must fully account for the interactive effects among earthquakes, waves, and the bridge structure itself.

4.5 Explosive-Seismic Loads

Among various accidental loads, seismic and explosive loads stand out for their destructive effects and distinct response times on bridge structures. Moreover, during an earthquake, the probability of explosions involving on-bridge pipelines and tank vehicles increases significantly. Studies have shown that the behavior of bridge structures under combined seismic and explosive actions shares similarities with that under single explosive loads, yet with amplified effects: under the combined action of longitudinal seismic waves and explosions, the damage area and depth of bridge piers increase to varying degrees, with the pier bases undergoing complete shear failure. Additionally, the damage to piers under transverse combined actions is more severe than that under longitudinal combined actions involving simultaneous explosions, exhibiting a larger range of shear failure at the pier bases [11].

4.6 Wind-Wave-Vehicle-Seismic Loads

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5. Conclusions

The action mechanisms and failure modes under single loads and coupled multi-loads exhibit significant differences. While current research has yielded notable findings regarding the mechanisms of various single loads and their coupled effects, it remains largely focused on single impact loads, with certain limitations persisting in the understanding of bridge structural failure behaviors under coupled multi-loads. In the field of coupled multi-load research, although it is widely recognized that combined loads exacerbate bridge failure, investigations into the mechanical responses and failure mechanisms of bridge structures under multi-field coupling remain insufficiently in-depth. For instance, bridge foundations subjected to coupled seismic and flood loads simultaneously bear seismic forces and flood scouring forces; similarly, the dynamic impact responses under combined vehicle and explosive loads involve complex interactions spanning geotechnical dynamics, fluid mechanics, and other interdisciplinary domains. Presently, existing research cannot fully or accurately unravel such intricate processes. Future studies should consider the multi-field effects of fluid-structure interaction loads, aiming to optimize bridge structural designs and enhance their disaster resistance capabilities.

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