buildings

Review

The Sustainable Development of Bridges in China: Collapse Cause Analysis, Existing Management Dilemmas and Potential Solutions

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Abstract: The construction of sustainable bridge projects has become a global mission and challenge in the 21st century. Unfortunately, there has been a rise in bridge collapse incidents due to various factors in recent years both during the construction and service phases. These incidents have resulted in significant loss of life and property damage, exacerbating the five sustainable development issues faced by bridge engineering: natural, resource, environmental, social, and economic factors. As a result, the prevention and resolution of bridge collapse accidents have garnered attention from professionals, research institutions, and government departments, making it a prominent research area. In line with the sustainable development concept of bridge engineering, this article classifies the causes of bridge collapses into two categories: those occurring during the construction phase and those happening during the service phase; the latter includes lack of inspection, maintenance and management, external natural factors, and human factors. Furthermore, this article thoroughly examines the existing national management framework, identifying the dilemmas that hinder its effectiveness in regulating bridge collapse prevention. Finally, several effective suggestions are proposed for the prevention of bridge collapse incidents. These recommendations aim to motivate governments, project owners, designers, constructors, managers, and users to actively develop and promote high-quality sustainable bridges.

Keywords: sustainable development; bridge collapse; cause analysis; regulatory dilemmas; potential solutions

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1. Introduction

Since the beginning of the 21st century, the challenges we encounter encompass not only the enhancement of the overall lifecycle performance of large-scale bridges but also the minimization of the adverse consequences of structural failure on human beings and society. In recent decades, China has achieved historic accomplishments in bridge construction and the mission and challenge of sustainable bridge engineering have become increasingly prominent. As of the end of 2022, China had a total of 1.032 million highway bridges (excluding the bridges in the regions of Hong Kong, Macau, and Taiwan) [1], and the construction quality and maintenance levels of bridges have been consistently improving over time. Nevertheless, bridge accidents may lead to substantial casualties, property damage, and severe social implications. Bridge collapses have occurred occasionally, caused by factors ranging from design, construction, and supervision during the construction phase, to external natural and human factors during the service stage (Figure 1). As an example, on 14 June 2019, the Zijin Bridge in Heyuan, Guangdong, collapsed primarily due to flood and bad management (Figure 2). It can be observed that the occurrence of these bridge collapse accidents goes against the principles of sustainability, resulting in the failure to acquire long-run growth and non-harm to future generations, along with significant direct and indirect economic losses, severe social impacts, and incalculable ecological imbalances. The incidents are directly associated with the design, construction, and operation stages, and sometimes even involve the planning and demolition stages.

Figure 1. Collapse of the Old Tacoma Narrows Bridge, Seattle, WA, USA (reproduced with permission from Olson D. and Hook J., *The Physics Teacher*; published by AIP Publishing, 2015) [2].

Figure 2. Collapse of the Zijin Bridge, Heyuan, Guangdong, China (reproduced from Tan et al, *Sustainability*; published by MDPI, 2020) [3].

Sustainability is defined as the satisfaction of the requirements of current demand without changing the future generations' needs, which can cover a wide range of measures for the improvement of operation performance of engineering, and ultimately serve as an extremely valuable tool in disaster prevention and decision making associated with different structural systems, such as buildings and infrastructure [4]. Sustainability can also be referred to as the Triple Bottom Line, which encompasses three key objectives: economic sustainability, social sustainability, and environmental sustainability. The framework of the concept of sustainable development [5,6] comprises one sustainable principle (prohibiting the extraction of materials beyond the capacity of natural replenishment), two sustainable goals (achieving long-term coordinated growth and ensuring non-harm to future generations), three sustainable indicators (ecological sustainability, economic sustainability, and social sustainability), four sustainable requirements (embracing innovation in conceptual design, implementing new technologies in construction projects, enhancing durability in structural operation, and prioritizing disaster control throughout the service life), and five stages (project planning, structural design, engineering construction, operational management, and comprehensive demolition) (Figure 3).

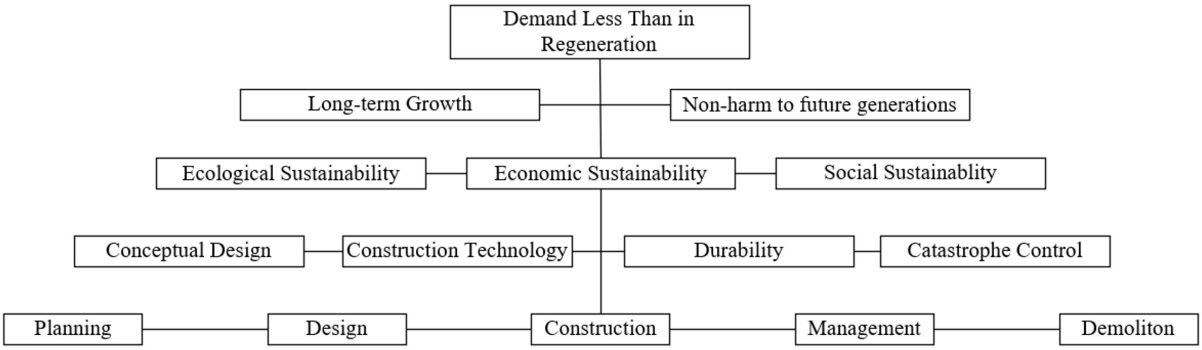

Figure 3. The framework of sustainable development of bridges.

To achieve the sustainable development of bridges, it is of utmost importance to prevent catastrophic sudden changes in bridge performance, such as partial or complete collapse. In his study, Head [7] aimed to enhance the durability, reduce the life cycle cost, minimize traffic disruption, and mitigate the environmental impact of bridges through the utilization of new advanced composite materials. Wu et al. [8] performed a study on the decision-making method for bridge maintenance with a focus on the concept of sustainable development. Dong [9] developed an approach addressing the risk, sustainability, and resilience from the perspective of the life cycle management of structural systems, with emphasis on various structural systems. Balogun et al. [10] suggest that bridge designers should focus on environmental considerations and enhance sustainability by integrating the whole life cycle assessment into the bridge design process. Xu and Guo [11] developed a condition-based highway bridge maintenance method aimed at maximizing reductions in total carbon emissions from bridge networks, taking into account budget constraints on maintenance. Padgett and Tapia [12] presented a method for a whole life cycle sustainability analysis (LCS-A) based on risk assessment to quantify environmental sustainability indicators for structures that face multiple threats.

It is important to acknowledge that China has made substantial efforts to address the issues associated with bridge collapse accidents. Several measures have been adopted to enhance the quality of bridge design, construction, and supervision, as well as to improve the management, detection, inspection, and maintenance procedures for bridges. These initiatives are aimed at preventing bridge collapses, mitigating risks, and ensuring the safety and reliability of bridge structures. Nonetheless, it remains crucial to continue conducting research and employing innovative approaches to minimize the occurrence of such accidents and their detrimental consequences. In an effort to enhance the safety and reliability of bridges and minimize the incidence of bridge collapse accidents, numerous scholars and experts have conducted comprehensive statistical investigations into the causes of bridge collapses [13–15]. The study of bridge collapse encompasses several disciplines, such as structural engineering, monitoring technology [16,17], transportation, and earthquake engineering, among others, and research methods employed in this area include theoretical analysis, experimental testing, numerical simulation, and case studies. The New York State Department of Transportation has established a comprehensive database comprising more than 428 collapsed bridges in the United States from 1992 to 2014. Cook and Barr [18] conducted an analysis of the condition and assessment levels of these bridges prior to collapse, identifying commonalities among them. Qin et al. [19] studied 123 hydraulic bridge failures in China from 1998 to 2018. Xu et al. [20] compiled a collection of 302 highway bridge collapses in China from 2000 to 2014, which were primarily caused by human factors.

Schaap and Caner [21] conducted a study on bridge collapses in Turkey, gathering data on over 80 incidents that predominantly occurred between 2000 and 2019. They identified the causes of these collapses. In a separate work, Deng et al. [22] categorized the primary reasons for bridge collapses into two main factors: natural and human. Stark et al. [23] analyzed the methods implemented to enhance the resilience of truss bridges.

The collapse causes of bridges are highly intricate, as evidenced by these studies. It can be attributed to various factors during the construction phase, including design, construction, supervision, maintenance, and reinforcement measures. External human factors, such as collisions, blasts, and overloads, as well as natural factors like earthquakes, floods, and scouring, also contribute to bridge collapses.

The collapse mechanisms of bridges have garnered significant attention among researchers and engineers. Bertolesi et al. [24] investigated potential collapse causes of the Augustus Bridge in Narni, Italy, specifically focusing on earthquakes. Choi et al. [25] developed a collapse cause analysis based on reliability theory, which accounts for uncertainties in order to accurately identify the causes of collapses. Salem and Helmy [26] conducted an analytical investigation into the cause of the Minnesota I-35W Bridge collapse, attributing it to design errors, maintenance issues, and traffic management. In another study, a discontinuum-based micro-modeling approach was used to explicitly explore potential collapse mechanisms based on the collapse of the Morandi Bridge in Genoa, Italy, on 14 August 2018 [27]. Zhang et al. [28] proposed a progressive collapse analysis of bridge structures, which utilizes a coupled simulation approach in both the structural and hydraulic fields to consider the threats of scour and floods.

Various technical recommendations have been proposed by scholars based on the analysis of bridge collapse causes. Schaap and Caner [21] suggested maintenance practices such as underwater inspections and flood event evaluations to minimize the probability of hydraulic bridge collapse, after assessing potential precautionary measures. Ozcelik and Tutus [29] brought forward essential recommendations for the construction of future bridges after investigating the reasons for the collapse of Botan Bridge (Siirt, Turkey). Based on investigations into continual high-strength bolt failures on steel truss bridges in China, Zhou et al. [30] discussed and summarized the typical reasons for failure and what can be done to prevent it. Proske [31] highlighted the significant impact of bridge collapses on the construction industry and suggested avoiding future failures by following preventative measures.

However, there has been relatively little research on the regulatory dilemmas related to bridge collapses, in comparison to the more comprehensive analysis of causes, mechanisms, and technical recommendations. London [32] presented eight case studies involving construction accidents caused by the failure of temporary structures, one of which is a parkway arch bridge, and illustrated the oftentimes unintended consequence of utilizing temporary structures, as well as the lessons that can be learned from their failure. Hick et al. [33] described the hospital system response to the I-35W bridge collapse. Seol and Jae [34] performed an investigation about crisis response and government responsibility in Korea. Patil et al. [35] conducted a study on how to minimize the socio-economic losses after the collapse. On 9 February 1971, the San Fernando Valley in Southern California experienced a major earthquake, during which a bridge connector ramp of a newly constructed freeway interchange collapsed and two men were killed, whose heirs sued the State of California and alleged that the highway was in a dangerous condition. The State defended itself by presenting evidence that the structure was built in accordance with reasonably approved engineering plans and standards, and successfully defended the use of these design criteria [36]. However, management problems related to the economy, culture, human health, and environment have consistently remained underappreciated and inadequately addressed for various reasons. This is often due to low project management levels and the resulting high security risks. Special management measures are needed to promote the sustainable development of buildings and infrastructure [30].

The aim of this paper is to investigate the causes of bridge collapse, analyze existing regulatory suggestions, and propose potential solutions. Through a comprehensive analysis of the causes of collapse, this study will examine both internal and external factors that contribute to bridge collapses in detail. Additionally, it critically examines several dilemmas regarding the existing regulatory framework and proposes suggestions for the prevention of bridge collapse. Finally, conclusions are drawn to enhance the sustainability performance of bridge engineering to the utmost extent.

2. Cause Analysis of Bridge Collapse

Throughout history, numerous bridges have collapsed due to various reasons [37]. In this study, the primary reasons for bridge collapses are classified into two categories: internal factors and external factors. Internal factors during the construction stage include quality defects resulting from design errors, construction mistakes, and supervision malpractice, among others. External factors during the service stage mainly include insufficient inspection, maintenance, and management (such as inadequate inspection and maintenance and vehicle overloading), external natural factors (such as earthquake, flood, scour, landslide, debris flow, hurricane, typhoon, tornado, wind, and tsunami), and external human factors (such as collision, fire, and blast).

2.1. Internal Factors during Construction Stage

2.1.1. Design Errors

In many instances, structural safety is jeopardized, and bridges may even collapse early on in the construction stage due to errors arising from inadequate design. Firstly, if design engineers have limited awareness and lack sufficient demonstration of design innovation, they may hastily implement immature techniques and ideas in actual engineering before detailed design schemes are discussed. Secondly, errors may occur during the design stage, such as incorrect calculations and blindly copying existing drawings. Thirdly, congenital deficiencies are attributable to underdeveloped theories, research, and standards that may have met specific requirements at the time. These deficiencies can potentially impact the safety and functionality of the structure [38]. For instance, the cause of the collapse of the Chirajara Bridge, which was a cable-stayed bridge still under construction, was attributed to a weakness in the tower's strength caused by a flawed design [39]. Lessons learned from incidents such as the collapse of the FIU pedestrian bridge in Miami, FL, USA [40] and the collapse of the Butou Bridge in Guangxi, China, due to excessively high abutments underscore the importance of prompt implementation of countermeasures when design errors lead to malfunctions.

2.1.2. Construction Mistakes

In recent years, bridge collapse accidents have become a common occurrence worldwide, often caused by construction-related factors. The use of malicious or substandard construction materials, as well as improper construction methods, can lead to poor construction quality falling short of design specifications. Moreover, construction equipment failure can also compromise construction quality. To prevent the collapse of asymmetric box-girder bridges or single-pier bridges, special emphasis should be placed on the overturning collapse mechanisms and the potential safety risks in existing bridges with similar geometries and same types [41]. The quality of construction materials plays a significant role in bridge safety [42]. For example, due to poor design and unsuitable construction processes, the Tuojiang Bridge in Hunan, China, collapsed on 13 August 2007 [43].

2.1.3. Supervision Malpractice

Engineering supervisors bear the responsibility of ensuring the proper implementation of construction plans. It is their duty to prevent any unauthorized modifications to the plans by the construction enterprise and to remain vigilant about quality issues during construction. The collapse of the Jinshan Bridge in Hubei province, China, on 19 November 2014, was attributed, in part, to supervision malpractices, as stated in the official report on the incident. An overview of bridge collapses that occurred during the construction stage due to internal factors is listed in Table 1.

Table 1. Overview of bridge collapses due to internal factors during construction stage in China.

Year	Bridge Name	Place	Fatalities /Injuries	Cause of Collapse
2000	Shenzhen Viaduct	Shenzhen, Guangdong	0/33	Construction mistakes
2002	Wangou	Nanyang, Henan	10/7	Construction mistakes
2005	Pearl	Zhunyi, Guizhou	16/3	Construction mistakes
2005	Xiaojianshan	Guiyang, Guizhou	8/12	Construction mistakes
2006	Tonganwan	Xiamen, Fujian	0/17	Construction mistakes
2006	Shunyi	Beijing	0/3	Construction mistakes, Design deficiency
2007	Tuojian	Fenghuang, Hunan	66/23	Construction mistakes, supervision malpractice, project owner interference
2008	Jintang	Ningbo, Zhejiang	4/0	Collision (vessel)
2012	Xingfulu	Hangzhou, Zhejiang	1/3	Construction mistakes
2013	Fengdu Yangtze 2nd	Chongqing	11/2	Construction mistakes
2014	Gaozhou	Maoming, Guangdong	11/16	Construction mistakes
2014	Hongkong-Macou-Zhuhai	Hongkong	1/4	Construction mistakes, supervision malpractice
2014	Jinshan	Enshi, Hubei	1/10	Construction mistakes, supervision malpractice
2016	Xiaozhuang	Kunming, Yunnan	2/4	Construction mistakes, supervision malpractice
2017	Longtan	Longyan, Fujian	0/7	Construction mistakes, supervision malpractice
2021	Hangyong Canal	Shaoxing, Zhejiang	0/0	Construction mistakes
2021	Nanmen	Jinhua, Zhejiang	1/0	Construction mistakes
2022	Xihuan interchange	Zhongshan, Guangdong	0/1	Construction mistakes

2.2. External Factors during Service Stage

An overview of bridge collapses that occurred during the service stage due to external factors is listed in Tables 2–4.

2.2.1. Lack of Inspection, Maintenance, and Management

(1) Inadequate inspection and maintenance

Bridges are subjected to long-term loads from pedestrians and vehicles, as well as harsh weather conditions. Consequently, they undergo degradation and fatigue, leading to various forms of damage such as cracks, pitting, peeling, exposure of steel bars, and corrosion. If the level of bridge inspection and maintenance is inadequate, the operational performance of bridges will gradually decline [44]. As deterioration accumulates beyond a certain threshold, bridges may encounter severe problems. An illustrative case is the I-35W Mississippi River Bridge [45], which exhibited severe corrosion in its supports as early as 1990 and was designated as “structurally deficient”, necessitating regular inspections and maintenance. In 2001, the bridge was found to have twisted and deformed longitudinal girders, with evidence of fatigue in the truss, indicating a collapse risk. Tragically, on 1 August 2007, at 6:01 pm during peak traffic hours, the bridge unexpectedly collapsed. This catastrophic event resulted in 13 fatalities and 145 injuries. However, by conducting systematic and thorough inspections and maintenance, the degradation process of structures can be slowed down, and potential structural issues can be identified before they escalate into severe damage.

(2) Vehicle overloading

Vehicle overloading, particularly in the transportation of heavy cargo, is a significant concern that requires careful consideration. With the increasing and intense competition in the transportation industry, vehicle overloading on highways has become widespread worldwide. This practice can result in fatigue-related issues in bridge components, leading to a shortened service life for bridges [46–48]. Moreover, it poses a threat to the safety of the bridges, and in extreme conditions, may even cause bridge collapses when the weight of the overloaded vehicle exceeds the ultimate bearing capacity of the bridge [49]. In recent years, China has witnessed a number of collapse accidents involving single-pier box-girder bridges, which were caused by the eccentric overloading of heavy vehicles. One notable incident is the collapse of the Huahu Interchange Bridge in Ezhou, Hubei, China, on 18 December 2021, which was a result of the transportation of a magnetic flow transformer using heavy-cargo vehicles [50]. To address this issue, several suggestions have been proposed. For instance, the adoption of a protection beam is recommended to mitigate the risk of overturning caused by over-height vehicles [51]. Additionally, ensuring lateral safety measures are in place is crucial for composite box-girder ramp bridges [52]. The collapse of the Yangmingtan Bridge has led to the provision of design recommendations aimed at preventing similar accidents caused by overloading [53].

Table 2. Overview of bridge collapses in China due to lack of inspection, maintenance, and management.

Year	Year Opened	Bridge Name	Place	Fatalities /Injuries	Cause of Collapse
2001	1990	Xiaonanmen	Yibing, Sichuan	3/3	Lack of inspection and maintenance
2004	1977	Tiantaizhuang	Panjin, Liaoning	0/0	Vehicle overloading Lack of inspection and maintenance
2006	1968	Tongyang Canal	Nantong, Jiangsu	4/5	Demolition risk
2011	1997	Third Qianjiang Bridge	Hangzhou, Zhejiang	\	Vehicle overloading, Lack of inspection and maintenance, Design deficiency
2007	\	Danla Express Viaduct	Baotou, Neimenggu	0/4	Vehicle overloading
2009	1995	Hongqi Road	Zhuzhou, Hunan	9/16	Demolition risk
2009	\	Jinjing Express Ramp	Gangtang, Tianjin	6/5	Vehicle overloading
2012	2011	Yangmingtan	Haerbin, Heilongjiang	3/5	Vehicle overloading
2015	2004	City south interchange	Heyuan, Guangdong	1/4	Vehicle overloading
2016	1991	Taihe	Ji'an, Jiangxi	3/5	Demolition risk
2018	1978	Heshui Bridge	Heyuan, Guangdong	1/3	Demolition risk
2019	2004	N0.312 National Highway Viaduct	Wuxi, Suzhou	3/2	Vehicle overloading
2021	2011	Huahu Interchange	Ezhou, Hubei	4/8	Vehicle overloading, Design deficiency
2021	1963	Xinhua Bridge	Zhuzhou, Hunan	0/0	Demolition risk
2021	1997	Huangnian	Danyang, Jiangsu	2/3	Lack of inspection and maintenance
2022	1990	Wenjiajie Bridge	Anshan, Liaoning	0/3	Vehicle overloading

2.2.2. External Natural Factors

China is a country that is prone to frequent natural disasters, including earthquakes, floods, scours, landslides, debris flows, typhoons, hurricanes, and tornadoes. The extent of the impact of these natural disasters on bridges depends on the specific type of disaster and the quality of bridge design and construction. To minimize the effects of natural disasters on bridges, it is essential to consider potential hazards during the design and construction stages and conduct appropriate safety analysis and design [54]. Regular inspections and maintenance are also crucial to ensure the structural integrity and stability of bridges.

(1) Earthquake

Earthquakes have a significant impact on the safety of bridges due to their sudden occurrence and immense destructive power, especially when bridges are not adequately designed to withstand seismic events. When an earthquake occurs, the bridges in the affected area suffer damage, disrupting essential transportation routes, impeding rescue operations, increasing loss of life and property, and presenting challenges to post-disaster recovery and reconstruction efforts. The seismic risks to bridges primarily involve four key aspects: collapse of the superstructure, damage to bridge bearings, destruction of bridge piers and abutments, and foundation failure [55,56]. For instance, during the Wenchuan earthquake, a total of 2105 bridges were damaged, with 450 railway bridges and 1655 highway bridges among them, resulting in significant economic losses.

(2) Flood

Flood disasters are one of the most common and destructive natural hazards, leading to chain reactions such as debris flow, landslides, and erosion. Flow conditions vary in different regions, making flooding a major cause of damage to highway and railway bridges. Bridge collapses due to floods are not uncommon, and frequent flood disasters, inherent deficiencies in foundation design, and human-induced changes in riverbeds are the primary culprits [57–61]. Data maintained by The New York State Department of Transportation show that, between 1992 and 2014, hydraulic-induced failure caused 55.4% of the 428 bridge collapses in their database [62], and a historical analysis of hydraulic bridge collapses is performed to check the relationship between bridge collapses and flood frequency or intensity [63]. In Europe, floods have caused 359 fatalities and resulted in a total economic loss of USD 67 million over the past decade [64].

(3) Scour

Scour refers to the destructive effect of flowing water, which, under certain conditions, causes significant changes in the geomorphology of riverbanks, beaches, and riverbeds through scouring. Due to factors such as reservoir construction, dredging, sand mining, and localized scouring of bridge piers, riverbed scour occurs, resulting in a reduction in the embedment depth of bridge foundations and affecting their stability. In the most severe cases, it can even lead to bridge collapse [65,66]. Furthermore, flood-induced scouring can pose a threat to the safety of masonry arch bridges [67].

(4) Landslide

Partial or total collapses of bridges may be due to the structural damage resulting from the slowly progressive displacements induced by various disaster sources, such as landslides [22]. Landslide refers to a natural phenomenon where the soil or rock mass on a slope, affected by various factors such as river scour, groundwater activity, rainwater infiltration, earthquakes, and human-induced slope cutting, moves downward along a certain weak surface or weak zone under gravity, either as a whole or in a dispersed manner [68]. Landslides can cause foundation settlement and even disasters such as bridge collapse. However, the time to failure of bridges affected by landslides can be predicted by combining satellite radar interferometry and numerical collapse simulation [69].

(5) Debris flow

As an extremely destructive geological hazard in mountainous areas, debris flow poses immeasurable losses and threats to people's safety due to its wide distribution and high destructive power when it occurs [70]. Generally speaking, debris flow mainly damages bridges through impact, scouring, abrasion, and burial. The enormous destructive power of debris flow disasters can cause severe casualties and substantial economic losses, leading to a slowdown in socio-economic development [71].

(6) Hurricanes, typhoons, and tornados

Hurricanes and typhoons are tropical cyclones in the northern hemisphere, generated in different oceanic regions, which can bring about disastrous impacts such as strong winds, heavy rainfall, and storm surges. Tornadoes are powerful cyclones that typically form when dry-cold air clashes with warm-moist air, often occurring in continental environments. Loli et al. [64] carried out a numerical study of a remarkable flood in Central Greece, which caused the collapse of many bridges and buildings following a Mediterranean hurricane in September 2020. The hydrodynamic forcing on bridge decks can be used to preliminarily assess the vulnerability of existing coastal bridges in hurricane-prone areas [72]. Hurricanes, typhoons, and tornadoes can cause significant vibrations on bridges, and in severe cases, bridge collapse [22].

(7) Wind

Aerodynamic vibrations, also known as wind-induced vibrations, are dynamic responses resulting from the interaction between wind and bridge structures. Based on different types of wind loads and interaction mechanisms, bridge aerodynamic vibrations can be classified into several types including flutter, vortex-induced vibration, jump, swing, and torsional vibration. Bridge aerodynamic vibrations not only affect the safety and durability of bridges but also pose dangers and discomfort to vehicular traffic and pedestrians, and can even lead to bridge collapse. The Tacoma Narrows Bridge [73] collapsed during a gale on 7 November 1940, and exhibited remarkable oscillations before collapsing spectacularly.

(8) Tsunami

A tsunami refers to a destructive sea wave generated by underwater earthquakes, volcanic eruptions, submarine landslides, or meteorological changes. The roaring waves, resembling icy walls, repeat every few minutes or several tens of minutes, causing devastation to seawalls, submerging land, claiming lives and properties, and inflicting immense destruction. The global occurrence of tsunamis generally aligns with seismic zones. On 11 March 2011, the Tohoku tsunami brought about great damage to various infrastructures in the northeast of Japan, and more than 250 bridges were destroyed by the rush of sea waters, such as the Utatsu Ohashi Bridge [74] and the Tsuyagawa Bridge [75].

2.2.3. External Human Factors

In recent years, with the rapid development of large-scale bridges across the sea and rivers, vessel or vehicle collision has become one of the important factors that influence the safety of large-span bridges. Some other incidents, for example, vehicle overloading, fire, war, and terrorist attacks, will also cause the bridge to undergo a massive loading exceeding the limit of bearing capacity in a very short time, damaging the structure, degrading the mechanical properties, and even causing the bridge to collapse.

Table 3. Overview of bridge collapses due to external natural factors.

Year	Year Opened	Name	Place	Fatalities /Injuries	Cause of Collapse
2023	1958	Xiaoqinghe	Beijing	\	Flood
2018	1984	Tonglu Corridor	Hangzhou, Zhejiang	8/3	Wind
1976	\	About 140 Bridges	Tangshan, Hebei	\	Earthquake
2021	\	Yematan 1#	Maduo, Qinghai	\	Earthquake
2021	\	Yematan 2#	Maduo, Qinghai	\	Earthquake
2019	\	Nanfangao	Yilan, Taiwan	6/12	Typhoon
2013	\	Niubizi	Deyang, Sichuan	0/0	Flood
2020	2012	Yaoheba	Ya'an, Sichuan	\	landslide
2022	\	Tonggu	Zibo, Shandong	\	Flood
2021	\	Xidahe	Wuchang, Heilongjiang	0/0	Flood
2021	2007	Xinxing	Ha'erbin, Heilongjiang	0/0	Collision (Ice)

(1) Collision

Inappropriate site selection and design can impede the smooth development of large-scale marine transportation, leading to frequent vessel–bridge collisions. Such accidents are caused by a variety of factors, including inadequate clearance height, insufficient horizontal clearance, and improper location in navigation channels. Therefore, a comprehensive evaluation of location, design, and other factors is necessary to ensure the efficient and safe operation of bridges in marine transportation [76–78].

The "Design Specification for Highway Bridge Anti-Collision" (JTG/T 3360-02-2020), released in 2020, explicitly states that the number of bridge collapse accidents caused by non-navigable span vessel collisions is nearly double that of collisions with the main navigable span. It is clear that the vessel collision issue for non-navigable span bridges demands significant attention. Publicly available data reveal that since 2007, there has been a total of 92 major vessel collision incidents with bridges in China, causing severe damage to the major transportation arteries. Therefore, implementing effective measures to prevent and manage vessel collisions with non-navigable span bridges is of utmost importance for ensuring transportation safety and maintaining the functionality of bridge infrastructure.

Compared to vessel collisions, vehicle collisions with bridges result in lower impact forces but occur more frequently. They typically occur in two scenarios: high-clearance vehicles colliding with the upper structures of bridges, and vehicles colliding with the sub-structures such as piers. Both scenarios have the potential to cause fatal damage to bridges [79–81]. In the United States, approximately 61% of rail bridges have experienced vehicle collisions, with prestressed bridges alone being struck over 160 times. Vehicle–bridge pier collisions are considered extreme loading hazards, as very large lateral impact forces can cause severe damage to superstructures, piers, or columns, and even lead to the collapse of the impacted bridge, as seen in the cases of the Taiyangbu Bridge [82] and the Jiujiang Bridge in Guangdong, China.

(2) Fire

Fires that result in the collapse of bridges are often caused by the impact of vehicles or by the collision between a vehicle and the bridge [83]. For instance, on 29 October 2012, a major fire accident occurred on the Mathilde Bridge in Rouen, France, resulting in the immediate closure of traffic [84]. These incidents underscore the importance of considering the potential for fires when designing and maintaining bridge structures, as they can have severe consequences on their structural integrity and overall safety.

(3) Blast

Military assaults, terrorist attacks, and occasional blasts may give rise to severe damage to bridges [85]. On 17 July 2022, the Crimean Bridge was destroyed, resulting in two deaths and one injury, and the interruption of transportation. Different researchers have studied the load effect of blasts on bridges. Farahmand-Tabar [86] modeled and analyzed a typical suspension bridge under explosion load. Carrillo et al. [87] presented and discussed the officially recorded bridge collapse incidents in Colombia by blast loading brought about by terrorist attacks from 1994 to 2014 and analyzed the economic, social, and political impact resulting from the collapse of the bridge located on the Riecito River in Caquetá.

Table 4. Overview of bridge collapses due to external human factors.

Year	Year Opened	Name	Place	Fatalities /Injuries	Cause of Collapse
2007	1988	Jiujiang	Foshan, Guangdong	9/2	Collision (Vessel)
2008	\	Jintang	Ningbo, Zhejiang	4/0	Collision (Vessel)
2010	\	Wulongjiang	Fuzhou, Fujian	0/18	Collision (Vessel)
2013	2001	Yichang	Sanmenxia, Henan	10/11	Explosion (Fireworks)
2022	About 1900	Wan'an	Pingnan, Fujian,	0/0	Fire
2023	2023	Hutuo River	Shijiazhuang, Hubei	0/0	Fire

2.3. Typical Bridge Collapses

2.3.1. Tuojiang Bridge

The Tuojiang Bridge [20] is situated in Fenghuang, Hunan. It is a four-span suspension chain hollow-girder arch bridge, with each span measuring 65 m. The overall length of the bridge is 328.45 m, and it has a deck width of 13 m and a pier height of 33 m. Tragically, on 13 August 2007, a severe collapse accident occurred during the construction of the Tuojiang Bridge, resulting in the loss of 64 lives, 4 serious injuries, 18 minor injuries, and causing a direct economic loss of CNY 39.747 million. The official report on this catastrophe identified the following causes of the accident:

- Constructor: The constructor seriously violated laws, regulations, and technical standards during the construction process of the upper structure of the arch bridge. The lack of reasonableness in the construction process resulted in the use of materials for constructing the main arch ring that did not meet the specifications and design requirements. This compromised the overall integrity and strength of the masonry.

- Project owner: There was a failure to strengthen management and inspection of construction, supervision, and safety processes. The construction schedule was blindly rearranged, leading to overstepped authority in commanding the construction and even requesting the supervision not to inspect the bridge.
- Supervision: The constructor's unauthorized modification of the original construction plan was not vigorously stopped, and during the stage of main arch construction, there was insufficient supervisory personnel. There was inadequate urging to rectify identified main arch construction quality problems. Frequent changes of on-site supervisory personnel could not ensure the continuity of the bridge supervision work.
- The survey unit and designer: The survey unit violated regulations by subcontracting geological survey projects to individuals. The early-stage geological survey work was not conducted in sufficient detail. Additionally, the on-site design services during construction were insufficient, and there was a lack of thorough communication.

2.3.2. The Taihe Bridge

The Taihe Bridge (Figure 4) is located in Ji'an, Jiangxi, and was completed in 1991. The total length of the bridge is 830.3 m, with an equal-sectioned catenary-shaped hollow concrete box arch consisting of 11 spans of 70 m. The main arch ring of the bridge is made of C30 concrete, with a section height of 1.3 m, a top width of 9.1 m, and a bottom width of 8.96 m. Piers 3 to 5 are gravity piers with caisson foundations, Pier 11 is a combined foundation abutment, and the others are excavated enlarged gravity piers and abutments. Piers 3 and 7 are reinforced piers. In 2012, the related inspection unit assessed the Taihe Bridge as a Class 5 bridge. On 11 September 2016, around 8:51 am, the bridge collapsed during the demolition process.

Figure 4. Collapse of Taihe Bridge, Ji'an, Jiangxi, China (reproduced with permission from Xu, X.; Wang, J.; Wei, J.; et al., *Engineering Structures*; published by Elsevier, 2018) [88].

According to the official report on this catastrophe, improper demolition construction on the top arch caused significant unbalanced horizontal forces on Piers 5 and 7, which directly led to their collapse. The intense unbalanced horizontal forces caused a strength failure in Piers 5 and 7, subsequently destabilizing the main arch ring, ultimately resulting in a "domino effect" collapse of the entire bridge.

2.3.3. The Third Qianjiang Bridge

Unlike the bridge collapse of the Yichang Bridge due to the blast of fireworks (Figure 5), which is located in Sanmenxia, Henan, China, the collapse cause of The Third Qianjiang Bridge, located in Hangzhou, Zhejiang, was overloading. The Third Qianjiang Bridge has a total length of 5700 m, including the main bridge of 1280 m and the north–south elevated approach bridge of 4420 m, featuring six lanes with two-way traffic. It was officially opened to traffic on 28 January 1997. On 15 July 2011, a partial collapse of the right-side lane of the main bridge's deck occurred on the Third Qianjiang Bridge's auxiliary bridge. A heavy-duty semi-trailer fell from the deck, also causing the collapse of the descending ramp. According to the official report on this catastrophe, the mistakes and responsibilities of each sector were summarized as follows:

- Overloaded truck: The main cause of the accident involving the Third Qianjiang Bridge was the overload of trucks, where the load effect of overloaded trucks exceeded the load-bearing capacity of the hollow slab beam.
- Maintenance unit: Overloaded vehicles frequently passed through the bridge for a long time, which was not effectively constrained. The maintenance unit did not pay enough attention to the daily maintenance work, resulting in large longitudinal cracks appearing along the joints of the hollow slab beam on the surface layer of the southern approach bridge.
- Designer: The designers of the bridge controlled the redundancy of the main bridge structure too tightly, and the dimensions of the box beam section were relatively small. The hollow slab beam adopted a shallow straight hinge joint structure, resulting in weak lateral load distribution effects, vulnerability, and poor repairability.
- Constructor: During the construction of the main bridge box beam, there were quality defects such as partial loss of vertical prestressing, insufficient pipe pressure grouting, joint mismatch, and rough surface with cracks.

Figure 5. Collapse of the Yichang Bridge, Sanmenxia, Henan, China (reproduced with permission from Wang, W.; Liu, R.; Wu, B., *Engineering Failure Analysis*; published by Elsevier, 2018) [85].

2.3.4. The Jiujiang Bridge

The Jiujiang Bridge is located in Foshan, Guangdong. It was completed and opened to traffic in 1988. With a total length of 1682 m, it is a prestressed concrete continuous box girder bridge with a main span of two spans and a 16-m span length, supported by a single tower cable-stayed structure.

On 15 June 2007, a cargo ship deviated from the main channel and collided with Pier 23, which was a non-navigation pier (Figure 6). This collision resulted in the collapse of Pier 23 and the collapse of approximately 200 m of the southern main bridge deck. Piers 24 and 25 were also pulled down and collapsed, with the collapsed Span 26 leaning against Pier 26. The cargo ship also sank. Four vehicles and two construction workers on the bridge fell into the river, resulting in eight deaths and one missing person. According to the official report on this catastrophe, the main cause of the accident was the sudden dense fog encountered during the ship's navigation. The ship's captain neglected to keep a proper lookout and took improper measures, leading to a unilateral responsibility accident of the ship colliding with the bridge.

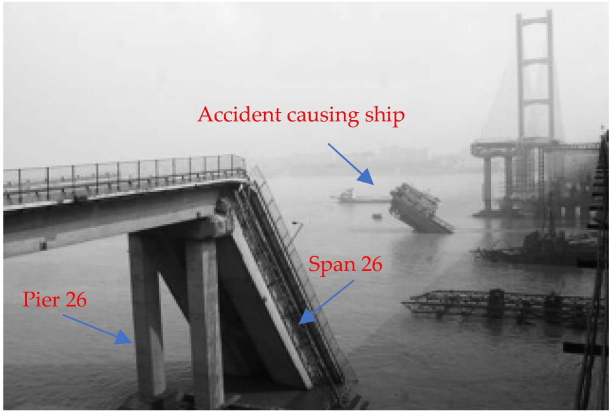

Figure 6. Collapse of Jiujiang Bridge, Foshan, Guangdong, China (reproduced with permission from Lu, Y.E.; Zhang, L.M., *Ocean Engineering*; published by Elsevier, 2013) [89].

3. Existing Regulatory Dilemmas in Addressing the Sustainable Development of Bridges

The failure of bridges has led to a great deal of urgency to examine the integrity and investigate the conditions of all bridges [45,90]. Due to the severe consequences and widespread social attention of bridge collapse accidents, the attribution of liability in such major accidents resulting from internal factors during the construction stage or external factors during the service stage has become a complex combination of regulations involving the coordination of various departments. Due to factors such as design, construction, maintenance, transportation management, natural disasters, and external human factors, bridge collapse accidents are inevitable in the whole lifetime of bridges. Therefore, an efficacious national regulatory framework is very important in dealing with bridge collapse risk. Though there are currently no specialized laws and regulations devoted to dealing with the issues of bridge collapse, there are several laws and regulations that may concern the regulation of bridge collapse. However, several shortcomings still exist within the existing regulatory framework, whose ability is obstructed, and the law challenges posed by bridge collapse cannot be effectively addressed.

3.1. Failure to Update the Bridge Design Specifications in a Timely Manner

The low level of safety provisions in China's structural design specifications can be attributed to the prolonged period of material shortage in the planned economy era. Today, the construction of civil engineering facilities is being carried out with standards from former impoverished and backward times. China's structural design specifications rely too heavily on past statistical data and do not adequately consider the potential future needs brought on by developments and improvements in production and living standards during the long-term use of structures. China's specifications stipulate a vehicle load safety coefficient of 1.4, which is lower than that of the United States (1.75) and the United Kingdom (1.733). As a result, the vehicle load effect design values that U.S. and U.K. bridges must withstand are, respectively, 40% and 59% higher than those required by China's specifications. On the other hand, when estimating the bearing capacity of bridge components, China's regulations set a relatively high material design strength, resulting in a design bearing capacity for China's bridges of only 68% and 60% of that for bridges in U.S. and U.K., respectively, with regard to vehicle load.

However, many of China's specifications have remained unchanged for many years. For example, the first two revisions of the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018) were made in 2004 and 1985, with revision intervals of 14 years and 19 years, respectively. In contrast, the United States revises its specifications every 3–4 years. The AASHTO LRFDBDS-9 LRFD Bridge Design Specifications (9th Edition) were released in 2020, with previous revisions in 2017, 2014, 2012, and 2007. Due to the delayed and missing specifications, many challenging issues encountered in the construction of new major bridges in China are being addressed through individual projects and scientific research. However, after accumulating numerous case studies, it is essential to elevate these research findings to a conceptual level and promptly summarize common elements. Additionally, in addition to design and construction, management and maintenance should also be regulated through special specifications.

3.2. Lack of Coordination between Laws and Regulations, Standards, and Specifications Related to Bridges

Within a country's legal system, different legal departments are responsible for the adjustment of laws based on their respective objects and methods of regulation. Additional legal norms, such as administrative regulations, rules, and the aforementioned national standards and industry norms, are established in accordance with the legislation (e.g., Legislative Law). The laws and regulations pertaining to bridge collapse primarily include the Construction Law, the Law on Production Safety, the Product Quality Law, the Road Traffic Safety Law, the Maritime Traffic Safety Law, the Regulations on Governance of Inland Waterway Traffic Safety, the Regulations on the Investigation and Handling of Maritime Traffic Accidents, the Criminal Law, and the Civil Code. These laws play a significant role in adjusting social relationships and regulating the behavior of legal entities within their respective domains. They can be referred to as the division of labor in legal norms, which encompasses both the division of labor in the content of legal norm texts and the division of labor in the implementation processes of legal norms.

In the early morning of 24 August 2012, less than a year after its opening, the approach bridge of the Harbin Yangmingtan Bridge in Harbin experienced a lateral slide collapse, resulting in the fall of four heavy trucks and the death of three people with five others injured. The investigation indicated that the design and construction of the bridge complied with national standards. However, a combination of factors, including modifications made to the trucks after leaving the factory, lax supervision during vehicle inspections, and flaws in handling vehicle overloading, led to the lateral slide collapse of the bridge. This incident involved a bridge that was fully compliant with national standards in terms of design and construction. Following the collapse, relevant authorities established a dedicated team of experts to investigate, and China Central Television (CCTV) provided detailed coverage. In the conclusion of the report, it was highlighted that if the overloaded inspection station had insisted on unloading the three trucks instead of allowing them to proceed with only a fine of CNY 450; if there had been proper adherence to vehicle production, licensing, and annual inspections according to the law; if previous similar accidents had received adequate attention; and if relevant authorities had taken the actual traffic conditions into consideration and implemented appropriate management measures based on the characteristics of the bridge, this tragedy could have been prevented. The occurrence of this tragedy effectively exposes the problem of insufficient integration between legal norms and design standards, resulting from a lack of effective coordination after the division of labor.

The coordination of laws is a guarantee of legal unity. For instance, new laws and regulations, such as the 2021 edition of the Constitution, require careful coordination with other laws and regulations, including the Criminal Law, Criminal Procedure Law, Civil Law, and Administrative Regulations, among others, to achieve legal unity. This coordination is necessary to effectively punish illegal activities and ensure safety in production. Similarly, newly issued Specifications for Maintenance of Highway Bridges and Culverts (JTG 5120-2021) should adhere to principles of combining prevention and control, scientific maintenance, safe operation, and smooth traffic flow. Furthermore, it should maintain coordination with national standards, industry standards of the Ministry of Transport, and standards from other relevant departments to ensure that bridges and culverts are in normal working condition. Unfortunately, in China, there are only two recommended standards related to building and house structures, namely, the Design Standards for Structural Anti-collapse of Buildings (T/CECS 392-2021) and the Risk Assessment Method for House Collapse Caused by Heavy Rainfall (YJ/T 14-2012), which currently lack mandatory provisions. While bridge collapse accidents are not uncommon, there still is not any formal design standard in place.

3.3. Ineffective Implementation of Laws, Regulations, and Standards

In the Huahu interchange ramp Bridge collapse incident, the trucks involved in the incident were subject to the Road Traffic Safety Law, the Regulations on the Management of Overloaded Transport Vehicles, the Implementation Plan for Carrying out Vehicle Overload Control Work Nationwide, as well as regulations issued by local governments. These regulations underwent a process of alignment and integration with the design and construction standards of the Huahu interchange ramp Bridge, including the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018), the General Specification for Design of Highway Bridges and Culverts" (JTG D60-2017), and the Specifications for Design of Foundation of Highway Bridges and Culverts (JTG 3363-2019). Additionally, these regulations also intersected with various national standards for building materials. In the specific case of the Huahu interchange ramp Bridge incident, there were no issues with the division and integration of the legal regulations on a textual level. However, there was a malfunction in the reorganization mechanism during the implementation phase.

The expert group investigating the accident determined overloading as the main cause of the bridge collapse. There are clear regulations in place for dealing with overloading in highway transportation, such as the aforementioned Road Traffic Safety Law (2021) and the Regulations on Governing Overweight and Overloaded Goods Vehicles in Shaanxi Province (2020). According to these legal regulations, combined with a fine, overloaded vehicles must be unloaded and their cargo must be transferred (except for transporting non-disassembled items with a valid permit for overweight transportation on highways). However, during highway operations, practices such as substituting fines for unloading, imposing fines without correcting violations, repeated penalties, accepting bribes, and allowing private vehicles to continue, have been observed. Under this fine-based management model, fines have become a form of tolls. Consequently, the legal norms pertaining to highway transportation have been reshaped into a set of distorted unwritten rules that currently govern China's highway network. These "new" rules usually only impact the lifespan of highways and increase maintenance costs, without attracting considerable attention until overloaded vehicles drive onto nationally standardized bridges, resulting in severe and unforeseen consequences. This illustrates the failure of reorganizing legal norms due to a lack of effective enforcement.

The ineffective enforcement of laws is a major reason for the failure of legal restructuring, and it is also a dilemma in China's legal system construction. At the macro level, China lacks local characteristics in its laws and regulations. In order to modernize the country, a large number of laws have been transplanted. At the micro level, this involves various interest issues in society, such as the non-conformity of interests between traffic roads as public consumer goods and truck drivers and regulatory departments, the irrationality of transportation supervision mechanisms, and the improper distribution pattern of the transportation industry's interests. In this context, any law that is not effectively enforced may encounter varying degrees of failure when it is restructured with related laws and regulations.

3.4. Inadequate Coordination by Functional Departments, and Lack of Timely and Transparent Information Disclosure

3.4.1. Functional Departments Have Not Exerted Sufficient Subjective Initiative

The formulation of legal norms, spanning from the manifestation of societal needs to the drafting of corresponding texts, and further culminating in the promulgation and implementation of these norms, entails a requisite amount of time. As a result, legal norms exhibit a certain degree of lag in responding to social phenomena. For instance, in the report by China Central Television investigating the Yangmingtan Bridge accident, one of the engineers involved in the bridge's design, Dongchao Sun, argued that incorporating considerations of overloading into bridge design poses a substantial challenge, given the elusive nature of overload limits. Consequently, identifying the parties responsible for tackling such practical issues that present difficulties for legal norms to comprehend remains a pertinent inquiry.

Within the fissure between the integration of legal norms with the realities of society, it becomes pertinent to determine which entity should effectively assume the role of examination, rectification, and supplementation. The present author contends that by perceiving bridges as ordinary consumer goods, the complexity of the issue could be somewhat simplified. In the case of ordinary commodities, disregarding proper usage may result in accidents ranging from minor appliance malfunction to grave personal injury, with users bearing the responsibility for non-quality-related damages. Likewise, bridges, with the non-specific general public as the intended users, necessitate standardized usage to safeguard public life and property. Therefore, the responsibility for disseminating the "correct usage methods" for these implemented bridges falls upon whom?

As an evident fact, the Yangmingtan Bridge represented a pivotal provincial and municipal construction project supported by governmental funding. Confronting uncontrollable circumstances such as overloading, the government should evaluate the real-time conditions of potentially overloaded cargo trucks on the road and use this information to establish a limit estimation as a load value for the bridge design. Additionally, the government should assume an obligation to notify cautionary rules regarding the use of the bridge. This entails the cooperation of verification units, traffic police departments, advertising departments, transportation departments, and other entities operating under governmental auspices that should harness their functional aptitudes to relay operational instructions and cautionary rules related to the bridge through diverse means of communication to cargo drivers. Moreover, from a broader perspective, the usage habits of these communal highway facilities must be assimilated as part of the driver's qualification exam. Consequently, governmental functional units bear unequivocal responsibility for failing to comprehensively assess actual factors that led to the Yangmingtan Bridge's collapse and the subsequent systematization of legal norms.

3.4.2. Insufficient Integration, Handling, and Dissemination of Accident Information by Relevant Departments

According to Heinrich's Law, behind a major accident with severe injuries, there are inevitably many minor incidents and a large number of hidden safety hazards. To prevent major accidents, it is necessary to reduce and eliminate non-injury accidents, and to attach importance to the early signs of accidents and attempted accidents; otherwise, a disaster will eventually be caused.

Prior to the collapse of the Huahu Interchange ramp bridge in Ezhou, there have been numerous incidents of bridge collapses caused by design issues of elevated bridges. For example, on 10 October 2019, the Xigang Road elevated bridge on the Shanghai-bound direction of National Highway 312 in Wuxi, Jiangsu, collapsed. On 19 June 2015, the exit ramp bridge of Guangdong Heyuan City South on the Guangdong–Ganzhou Expressway tilted. On 24 August 2012, the Yangmingtan Bridge in Harbin collapsed. On 24 October 2007, the elevated bridge connecting Ethnic Dong Road to the Danla Highway exit in Baotou experienced a side tilting collapse. At 1:33 a.m. on 16 July 2009, at a distance of 800 m east of the Tanggu Toll Station on the Tianjin–Jinzhong Expressway, a ramp bridge suddenly collapsed. On 21 February 2011, in the early morning, the approach bridge of the Chunhui interchange bridge in Shangyu, Zhejiang collapsed. From these not-uncommon accidents, it can be seen that the main reasons for the overturning of the elevated bridge deck are as follows: (1) Overloading of trucks on the bridge. (2) Use of single-pier design for bridges. (3) Sudden or continuous concentration of overloaded trucks on the same single-side lane.

According to Article 16 of the Provisions on the Administrative Responsibility for the Investigation and Punishment of Major Safety Accidents by the State Council (2001 version), after a major safety accident occurs, the relevant governments at all levels and government departments should immediately report it in accordance with the procedures and time limits. Based on this regulation, major safety accidents in various regions should be reported to higher-level governments and investigated. Therefore, the higher the level of the government agency, the more extensive the information they have on safety accidents and the greater the opportunity and ability to integrate and process this information. After these higher-level governments and the State Council integrate the relevant accident information, they should convey this information to the governments and relevant functional departments within their jurisdiction, conduct inspections for similar accident hazards, and take timely preventive and remedial measures for public goods with safety hazards. If, after a series of bridge collapse accidents, the causes of bridge overturning were addressed by coordinating government departments, relevant remedial and preventive measures would be taken, such as reconstructing bridge structures, prohibiting single-pier bridges from being loaded above their approved weight limit, and placing signs at bridge entrances to remind drivers not to drive in the lanes close to the edge of the bridge. In that case, the tragedy at the Huahu Interchange in Ezhou would not have occurred.

3.5. Inadequate Measures for Disaster Prevention and Mitigation in Bridges

As mentioned earlier, frequent accidents of bridge collapse occur due to natural disasters such as earthquakes and floods. Disaster prevention and mitigation for large-scale bridge structures heavily rely on the health monitoring and safety control of the bridge structures. Research in this field has become a hot topic internationally, primarily due to the progress in infrastructure construction and related disciplines in developed countries. At the end of 1987, the United States, Japan, and other countries jointly proposed a resolution to the 42nd United Nations General Assembly, which was passed and formed Resolution 169, officially designating the last decade of the 20th century (1990–2000) as the International Decade for Natural Disaster Reduction. To support this initiative, the State Council of China established the China International Decade Committee for Disaster Reduction, consisting of 28 ministries and bureaus. Later, it was renamed the China International Committee for Disaster Reduction to coordinate and organize comprehensive disaster prevention and mitigation actions. A series of significant disaster prevention and mitigation projects were implemented as part of these efforts.

In 1997, China enacted the Earthquake Prevention and Disaster Reduction Law with the goal of defending against and mitigating earthquake disasters, protecting people's safety, and promoting sustainable development economy and society. Additionally, 55 provinces and cities were subsequently issued regulations on earthquake prevention and disaster reduction. In 2008, following the Wenchuan earthquake, China revised the Earthquake Prevention and Disaster Reduction Law and increased its support for research on disaster prevention and mitigation of earthquakes and other natural disasters.

In 2007, the National Natural Science Foundation of China approved the launch of the first major research program in the field of civil engineering in China, entitled Dynamic Catastrophe of Major Engineering Works. This program focuses on the dynamic catastrophe response of three types of major engineering works under strong earthquakes and strong/typhoon forces. Its aim is to provide a theoretical foundation and technical support for ensuring the safe construction and operation of major engineering works in China. However, health monitoring and safety control in this field are characterized by strong interdisciplinary aspects, a high proportion of new technological components, and substantial investments in application.

Currently, the main research challenges lie in the slow progress of structural damage identification theory due to the complexity of bridge structures, and there have been limited breakthroughs in structural condition assessment methods. The majority of research and applications have primarily focused on the application of monitoring technologies and systems, while the assessment of bridge conditions still relies on traditional methods. Although China's large-scale bridge construction has a relatively short history, the significant scale of construction, rapid development, and issues with design specifications and construction quality have brought about hidden risks in aspects such as structural safety, durability, and functionality.

With the development of the Internet of Things (IoT) and sensing technology, bridge safety monitoring work has gradually transitioned from manual periodic inspections and measurements to a monitoring mode that combines manual periodic inspections and measurements with automated real-time monitoring. The development and application of automated monitoring technology make it possible for the digital transformation of transportation infrastructure in our country, to a certain extent, addressing issues such as subjectivity, insufficient accuracy, random factors, and poor timeliness in manual inspections. It also provides technical support for structural behavior tracing and prediction. However, the development and application of automated monitoring technology are dependent on the comprehensive utilization of interdisciplinary knowledge in communication, sensing, data processing, and mechanical analysis. Each of these technological bottlenecks directly affects the application effectiveness of automated monitoring technology.

Based on the current application status of bridge health monitoring projects in China, there are several shortcomings in the current stage of automated monitoring technology: (1) the raw data obtained during the monitoring process did not receive effective processing and application, and even the authenticity and reliability of some monitoring data were questionable, leading to a large accumulation and wastage of data; (2) low efficiency in data application and an inability to timely and effectively guide practical maintenance decision making; (3) the reliability and authenticity of measurement data gradually decrease year by year as the lifespan of sensing devices increases; and (4) a systematic framework for bridge structural safety assessment has not yet been established, and further improvements are needed in terms of information interaction and joint application between results from manual inspection and automated monitoring.

4. Suggestions for the Prevention of Bridge Collapses

In order to reduce the occurrence of bridge collapse accidents, guarantee the safety of bridges, and achieve sustainable development, the following regulatory measures are recommended.

4.1. Completely Eradicating Design Errors and Construction Mistakes

As mentioned above, the strength and redundancy rate may be not enough because of design errors. To avoid design errors, it is crucial to start from the source.

First, during the process of bridge design, it is very important to incorporate appropriate safety redundancy rates for structural strength and enhance the safety coefficients for unforeseen and causal events such as earthquakes and floods, which will strengthen the capacity of bridges to withstand natural disasters. Comprehensive consideration also should be given to the surrounding environment, geography, climate, and future traffic volume developments when designing bridges. Moreover, it is imperative to reinforce control measures throughout the full life cycle maintenance and retrofitting processes, ensuring the proper implementation of quality inspections for these particular procedures. The maintenance and renovation must be entrusted to professional design engineers while strictly controlling the workflow and adhering to a rigorous process involving bridge-specific inspection, design, construction, and completion of acceptance.

Second, another way that should be considered is to strengthen the quality control and management of bridge construction. It is vitally important for involved organizations to place high importance on the quality management of bridge construction. To protect people's lives and property, it is essential to carry out the whole process of bridge design, construction, and management with a strong commitment. The implementation of an effective engineering quality accountability system is of utmost importance, and the responsibilities and corresponding individuals of all participating units in the project should be clearly defined. Quality objectives should be established, and a sound quality control system comprising government regulation, social supervision, and self-inspection by enterprises should be established. Additionally, it is necessary to strengthen the review of construction plans, conduct comparative evaluations and the optimization of design schemes in a scientific manner, and enhance the control over the construction quality at every stage of concrete production, transportation, pouring, and maintenance. Efforts should be made to control testing, inspection, and construction monitoring, further improving the quality of bridge construction and achieving long-term management objectives. The aim is to eliminate common quality issues in bridge construction, prevent quality problems, and ensure the quality and service life of bridges.

Third, to address inherent deficiencies in structural design, the scientific research and theoretical level of bridge structural studies should be improved. Furthering scientific research on new materials, technologies, techniques, and management practices is essential. Bridge design, construction, and maintenance specifications need to be continuously revised to incorporate novel concepts, design methods, and standards based on relatively new theoretical foundations and practical experience. Additionally, it is crucial to implement the management of disaster prevention and undertake maintenance renovations on existing infrastructure while establishing a scientific evaluation system. Furthermore, systematic scientific research is needed to understand bridge disasters, focusing on the comprehensive analysis of water-induced disasters, earthquakes, and unforeseeable hazards.

4.2. Promoting the Level of Bridge Management and Maintenance

Enhancing bridge maintenance and management standards and strengthening transportation oversight are essential to ensure the safe operation of bridges.

First, establishing well-defined transportation management and maintenance systems and enhancing real-time monitoring of vulnerable and major bridges are essential. By adopting the devices and technologies of the Internet of Things (IoT), establishing a systematic maintenance system, and creating a maintenance management database for bridges, comprehensive records can be maintained on the operational and maintenance conditions of bridges. This enables the realization of an intelligent, efficient, and secure smart bridge maintenance and management system, ensuring the traceability of monitoring data [91]. The system aims to achieve real-time assessment, intelligent management, improved efficiency, proactive warning, closed-loop integration, and precise safety, ultimately enhancing the quality and efficiency of bridge maintenance. Furthermore, it facilitates the informatization, intelligentization, and intensification of bridge maintenance operations, thereby reducing the occurrence of severe bridge accidents. For example, Lee and Sternberg [92] proposed a new system for preventing bridge collapses, one that monitors and reports on bridge performance and bridge failures electronically through smart sensor networks incorporated into bridges.

Second, the passage of overloaded vehicles on bridges imposes substantial load effects on the structures, consequently intensifying the aging and deterioration of the bridge. By fostering interdepartmental collaboration, a stringent crackdown will be implemented to eliminate overloaded and over-limit transportation. Emphasis will be placed on bolstering upfront management of oversized transports to avert risks in the early stages. Transportation enterprises should be encouraged to operate lawfully while promoting safety-conscious transportation practices. Furthermore, transportation scrutiny and management will be reinforced, with the transportation department standardizing the approval process for transport permits, and the public security and traffic management authorities strictly scrutinizing factors associated with over-limit transportation. Additionally, government supervision will be intensified, emphasizing the regulation of overloaded and over-limit transportation, applying more severe penalties, and implementing bridge risk investigations, rectification, and reinforcement measures.

Third, to mitigate the risks of vehicle and vessel collisions, fires, and explosions, the safety facilities of bridges should be improved. The management department of bridges should conduct round-the-clock monitoring of traffic activities in bridge areas, establish an emergency response system, and enhance the implementation of anti-collision energy-absorbing devices around bridge piers. Warning signs must be installed in the vicinity of these devices. Drivers must exercise carefully when navigating, slowing down in advance, and ensuring the safety of both vessels and bridges. Buffering and flexible anti-collision devices or intelligent monitoring and early warning systems are implemented for piers in navigable and adjacent non-navigable areas. Height restriction facilities are provided at intersection points. Bridges are treated with fire-resistant coatings as structural protection and utilize new refractory cement and binders to enhance high-temperature resistance, preventing severe damage and accidents. After a fire, a comprehensive evaluation of the bridge's condition should be conducted, following relevant standards to determine whether reinforcement, repairs, or demolition are needed.

4.3. Strengthening the Prevention and Control of Natural Disasters

To safeguard the external safety of bridges, it is crucial to enhance the prevention and mitigation of natural disasters and proactively eliminate safety hazards at their origins.

First, it is important to fully comprehend the importance of disaster prevention and mitigation, particularly in ensuring the safety of urban bridges, which is essential for protecting lives, and property, and fostering sustainable development in China. Given the increasing frequency of extreme weather events, recurring seismic disasters, and the potential for human-induced calamities in recent years, it is imperative to prioritize this task as an enduring and formidable responsibility by intensifying research efforts in the realms of bridge construction, management, and technology. Establishing a comprehensive bridge engineering safety management framework across the entire life cycle, encompassing design, construction, operation, and monitoring, is imperative to ensure the smooth progress of bridge projects throughout their life spans.

In order to promote disaster prevention and management, as well as maintenance and rehabilitation of existing urban bridges, it is essential to establish a scientific evaluation system, which should include strengthening research on vulnerability under disaster conditions, establishing scientific and quantitative databases for durability and service life, continuously enhancing disaster warning and defense capabilities, and actively engaging in resilient design for urban bridges. Efforts should also be directed toward conducting research on enhancing bridge safety reserves. The development and enhancement of design standards and local regulations for disaster prevention and mitigation are crucial to effectively tackle severe disasters, alleviate the overload condition of urban bridges, and prevent the deterioration of material and structural performance caused by aging, corrosion, and cyclic loading fatigue. Furthermore, detailed investigations and inspections of existing urban bridges should be conducted.

Third, newly constructed bridges should be designed according to higher flood control standards, while existing bridges require strengthening in terms of management, maintenance, and retrofitting. Historic girder and arch bridges are often the ones that are washed away during the flood season, due to their deteriorated performance caused by their age and repeated heavy rainfall. Maintenance units should prioritize measuring the impact of riverbed erosion and gaining a comprehensive understanding of the erosion depths associated with a bridge's general and local foundation, thereby conducting regular inspections of the underwater foundation. It is recommended to monitor the service life of aging bridges, measure new flood resilience indicators, and accordingly carry out reliable maintenance, reinforcement, and protection measures.

Finally, to enhance the resistance of bridges against seismic and wind events, it is important to implement performance-based design and improve the structural resilience to disasters. If a bridge under maintenance incorporates cable-stayed structures, the maintenance unit should pay close attention to the impact of bridge wind-induced vibrations.

After a typhoon passes, specific inspections should be conducted on relevant components to prevent any potential hazards. The maintenance unit should take proactive measures and develop emergency response plans for bridges in their jurisdiction that may be at risk of landslides. It is also essential for the maintenance unit to hold a clear understanding of the seismic resistance level of the bridges within their jurisdiction and whether they meet the new seismic requirements. If necessary, seismic strengthening measures should be carried out. Sufficient safety redundancy should be considered during the design process, taking into account both natural and human factors. Moreover, the design of bridges should take into consideration various factors such as the surrounding environment, geography, climate, and future trends in traffic volume development.

5. Conclusions

In this paper, a concise yet relatively comprehensive investigation is proposed to examine the causes of bridge collapses, existing regulatory dilemmas, and potential suggestions for disaster prevention. The following conclusions are drawn:

(1) It is evident that the primary reasons for bridge collapses can be classified into two categories. Firstly, internal factors pertain to quality defects during the construction stage. Secondly, external factors primarily include a lack of inspection, maintenance, and management, as well as natural factors and external human factors. It should be noted that different types of bridges are vulnerable and sensitive to different causes.

(2) The current national regulatory framework exhibits several disadvantages and drawbacks that may impede its ability to effectively tackle relevant challenges. These include failure to update the bridge design specifications in a timely manner; lack of coordination between laws and regulations, standards, and specifications related to bridges; ineffective implementation of laws, regulations, and standards, inadequate coordination by functional departments; lack of timely and transparent information disclosure; and inadequate disaster prevention and mitigation measures for bridges.

(3) Relevant reforms and innovations are needed to promote the formulation of a more effective national regulatory framework for the prevention of bridge collapse. Some suggestions are recommended, mainly including completely eradicating design errors and construction mistakes, promoting the level of bridge management and maintenance, and strengthening the precaution and control of natural disasters.

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