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Review

State-of-the-Art Review of the Resilience of Urban Bridge Networks

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Abstract: With the rapid advancement of the urbanization process, the bridge networks in cities are becoming increasingly optimized, playing an important role in ensuring the normal operation of cities. However, with the gradual deterioration of bridges and the further attenuation of their capacity, many bridges are prone to damage or even collapse under extreme loads. After a natural disaster or human-derived accident occurs in a city, the normal operation of the bridge network in the city will play an irreplaceable role in emergency rescue and long-term recovery after the disaster. In this paper, the resilience of urban bridge networks, as a comprehensive indicator that integrates predisaster early warning, disaster response and postdisaster recovery information, is considered. This indicator has been applied in many disciplines, such as civil engineering, sociology, management and economics. The concept of resilience is expounded, and functional and resilience assessment indicators for bridge networks are established. Additionally, the research progress on bridge network resilience is described. Finally, combined with research hotspots such as big data, artificial intelligence and bridge structural health monitoring, the development trends and prospects of bridge network resilience research are discussed.

Keywords: resilience; bridge network; multihazard; structural health monitoring of bridge

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1. Introduction

With gradual improvements in social and economic levels, the current mode of urban construction is changing from rapid expansion to high-quality development. Additionally, over time, the density of the population, abundance of medical resources and social wealth have greatly increased. In this context, urban expressway networks and rail transit networks have become increasingly improved. As a result, large-scale and highly concentrated urban bridge networks have been formed. However, in harsh urban environments, many aging bridges are damaged and cracked due to insufficient durability. Bridge defects have become increasingly serious, and the number of dangerous bridges is increasing yearly [1]. It is predicted that by 2035, the proportion of bridges over 30 years old in China will reach 62.7% [2]. For such bridges, the structural mechanical performance can significantly deteriorate, and the disaster resistance capacity will sharply decrease.

In addition, in recent years, natural disasters and man-made accidents, such as earthquakes, floods, typhoons, fires and explosions, have occurred frequently in China, leading to serious safety hazards for cities. If a disaster or accident occurs in a city, it can cause varying degrees of damage to the urban bridge network, which is difficult and time-consuming to repair, resulting in serious traffic congestion or even interruptions in the complex urban traffic system. These issues will deeply affect the rescue and relief work of emergency departments after the disaster, resulting in considerable casualties, economic losses and social impacts. For example, the 2004 M9.3 earthquake in Sumatra, Indonesia, triggered a tsunami that affected more than 300,000 people in 12 countries [3]. The 2008 Wenchuan earthquake caused 69,225 deaths, 379,640 injuries, 17,939 disappearances and direct economic losses of approximately USD 100 billion [4]. Hurricane Sandy severely affected New York City's transportation system and caused more than USD 70 billion in economic losses in New Jersey and New York [5].

Therefore, in the face of various natural disasters and emergencies, determining how to effectively evaluate urban bridge networks has become an important scientific issue. In traditional research, the focus was on the safety, applicability, durability and robustness of individual bridges, and comprehensive evaluation indicators for bridges' predisaster prevention and control, disaster resistance and postdisaster recovery under disaster loads are lacking. To this end, countries around the world have begun to focus on resilience.

In 2011, the National Research Council of the United States proposed the goal of achieving 'national resilience' [6], with the objectives of strengthening cities' ability to respond to disasters and reducing urban losses due to disasters. In 2013, the Rockefeller Foundation began to implement the 100 Resilient City Project, which aims to help cities around the world enhance resilience [7]. In the same year, Japan promulgated the 'Basic Plan for National Territory Strengthening and Resilience' to further emphasize the security capabilities of cities considering the effects of disasters [8]. In 2015, the Third UN World Conference on Disaster Risk Reduction promulgated the 'Sendai framework for disaster risk reduction 2015–2030' [9], and Ban Ki-moon noted that improving resilience is one of the four key development areas of the United Nations Development Programme over the next 15 years. In 2017, the World Bank and GFDRR launched the City Resilience Program, which aims to support the development objectives of countries around the world and accelerate poverty reduction [10]. In 2020, the United Nations International Strategy for Disaster Reduction launched the 'Making Cities Resilient Campaign' [11]. In 2021, the Arup Group issued the 'Urban Resilience White Paper' to help global cities plan ahead and respond to future challenges [12]. In addition, in the past few years, China has taken the initiative to plan a resilient urban development strategy and actively pursued international cooperation measures. Therefore, the construction of resilient cities is rapidly occurring, as shown in Figure 1.

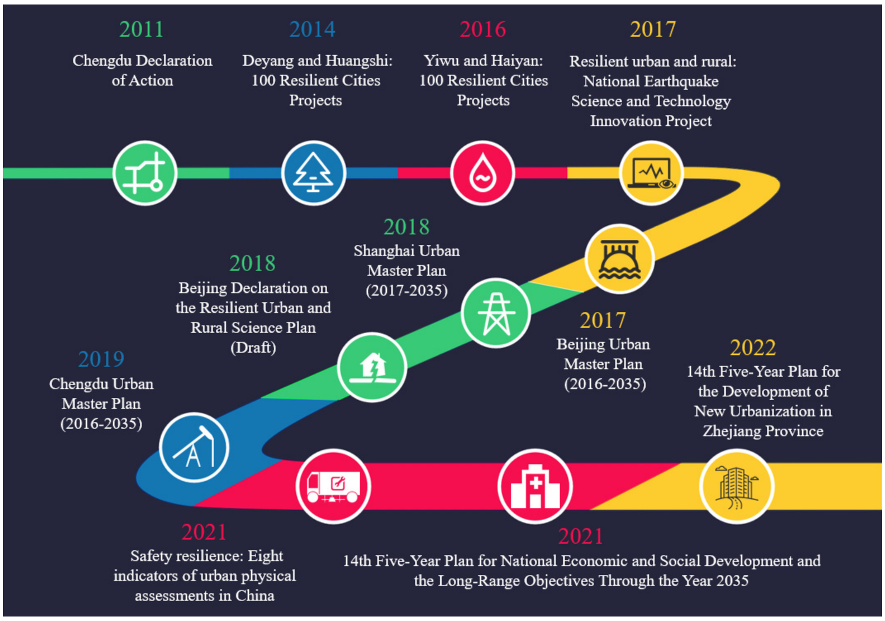

Figure 1. The resilient city development process in China [13–22].

The above discussion indicates that countries around the world have made great achievements in establishing macropolicies for resilient city construction. However, resilient cities are still at the conceptual level. As a research focus in civil engineering and transportation engineering, urban bridge networks are difficult to examine in many cases.

Notably, the variation and evolution process of bridge structural resilience under disaster loads must be studied, and the coupled evolution mechanism of single-bridge resilience and bridge network resilience must be assessed from an engineering perspective.

In this context, aiming at the complex characteristics and practical problems of urban bridge networks, a fast and efficient bridge network resilience evaluation index system and recovery model must be developed, and a bridge network resilience improvement method should be proposed. These techniques can provide academic and practical application value to ensure the safe operation of urban bridges, protect the safety of people and property and prevent and mitigate major urban risks.

2. Concept of Resilience

Resilience, or the ability to 'rebound' [23], is widely considered in mechanics, indicating the ability of a component to return to its previous state after deformation under an external force. In 1973, Holling first applied resilience in the field of systems ecology to characterize the ability of ecosystems to remain stable [24]. Since then, resilience has been widely used in research in various fields, such as construction [25], transportation [26,27], medical treatment [28], water supply [29], electricity supply [30] and gas supply [31].

Many scholars have defined resilience from different perspectives based on their respective research fields. Timmerman [32] defined resilience in 1981 as the potential of urban communities to resist external disturbances and recover from various disturbances. Bruneau [33] defined the seismic resilience of communities as increasing the capacity for earthquake risk control, reducing the levels of earthquake damage and loss and improving the ability to rapidly recover after an earthquake. That is, considering the four dimensions of technology, organization, society and economy, the structural failure probability, postdisaster loss and recovery time are calculated from the perspectives of robustness, redundancy, resourcefulness and rapidity to fully explain the seismic resistance of a community, as shown in Figure 2. This definition of resilience is currently the most recognized and widely used in the academic community. Francis et al. [34] believed that resilience, absorption and recovery are the three main characteristics of resilience analysis. Ribeiro et al. [35] suggested that urban resilience is the ability of a city or a certain subsystem of a city to resist disturbances by natural disasters, man-made disasters and emergencies, reduce the resulting losses and adapt to new conditions. The seismic resilience of buildings is defined by the Chinese standard GB/T 38591-2020 as the ability to maintain and restore the original function of a building influenced by earthquakes at a given level [36]. Although scholars in different fields use different definitions of resilience when solving urban resilience issues, the core concept of 'resilience' is consistent among various fields; that is, the ability of a component, structure or system to resist interference and return to its original state after being disturbed by external factors.

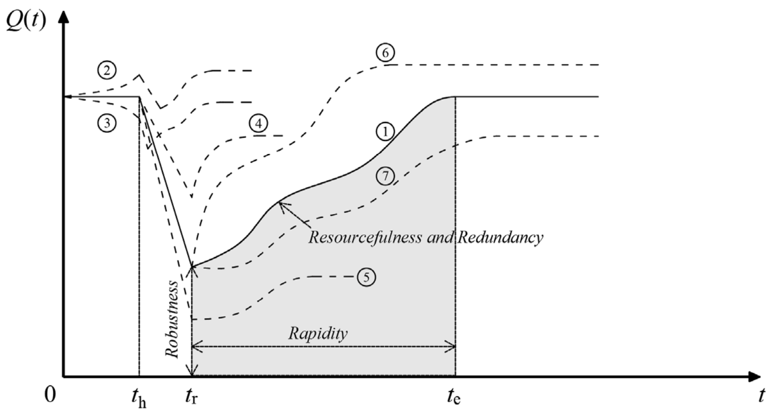

Figure 2. Conceptual diagram of resilience (Adapted with permission from Ref. [37]. 2020, Zou and Chen).

At present, no definition of urban bridge network resilience is available considering the effects of multiple disasters. Based on the core idea of resilience, this paper extends the concept of resilience to urban bridge networks and expresses the resilience of urban bridge networks as the comprehensive ability of a network to resist disasters, recover after disasters and withstand future disasters when it is subjected to multiple disaster loads at the same time, in turn or at multiple times.

The functional variations that urban bridges experience in relation to disasters can be divided into three stages: prevention, response and recovery. The meanings of functional curves ①~⑦ are given in Table 1. In the prevention stage, with increasing bridge operation time, increasing vehicle loads and the effects of adverse environmental conditions, existing urban bridges are considerably impacted; specifically, degradation can be serious and rapid. If a bridge is not appropriately maintained and strengthened in this stage, it will seriously affect the safety of the urban bridge structure and result in bridge function decline. In the response stage, the degree of bridge network function reduction depends on the hazard level of the disaster load, the structural fragility of the bridge [38] and the resulting impact on the bridge network [39]. In the recovery phase, the speed and effectiveness of functional recovery vary based on the characteristics of the bridge network and the different resources available for emergency rescue and bridge repair after a disaster [40]. This stage is one of the significant differences between the resilience of a bridge network and the risk of a bridge network because, for resilience, we not only study the probability of disasters and the consequences of bridge network failure but also focus on how to make decisions quickly after disruptions occur; that is, use the existing resources to enhance the engineering system and allow society to adapt to environmental changes as soon as possible [41–43].

Table 1. Various definitions of bridge network functional curves in the context of disasters.

Function Curve Number	Explanation
①	Reference curve
②	Predisaster maintenance and reinforcement
③	Bridge durability decline
④	Low hazard or low fragility
⑤	High hazard or high fragility
⑥	Adequate recovery resources or high redundancy
⑦	Limited recovery resources or low redundancy

Therefore, focusing on the three stages of the evolution of bridge network functions under disaster loads, it is necessary to propose a reasonable functional index to characterize bridge networks and, on this basis, to construct an accurate bridge network resilience evaluation index; such an index is a necessary prerequisite for calculating the resilience of urban bridge networks under disaster loads. Accurately establishing theoretical models of various disaster loads, efficiently analyzing the fragility of large-scale bridge networks in multiple disaster scenarios and proposing an optimal postdisaster recovery model under limited resource conditions are the core steps in calculating the resilience of urban bridge networks subjected to multiple disasters.

3. Bridge Network Function Index and Resilience Evaluation Index

When evaluating the resilience of urban bridge networks, to comprehensively examine the functional changes in the related systems before and after a disaster, it is necessary to first select indicators that reasonably characterize the functional characteristics of these systems. By analyzing the changes in traffic network functions, a resilience assessment can be performed.

3.1. Function Index

After a disaster, in the emergency stage, the most important role of the bridge network is to support the transportation of injured individuals to medical facilities in the shortest time possible; therefore, the most important concern at this stage is the accessibility of and travel time in the bridge network to minimize casualties. In the recovery phase, the most important role of the bridge network is to support post-earthquake urban recovery and long-term development; in this phase, focus is placed on production and economic, social and environmental factors, among others.

Nielson [44] suggested that accessibility is a good indicator for measuring transportation networks. Viriyasitavat [45] studied the reliability and fragility of road networks using topological connectivity as a functional indicator. Based on network topology connectivity, Zhang et al. [46] proposed the weighted emergency connectivity efficiency function index for the emergency phase and constructed a function index based on travel time and travel distance for the recovery phase. Capacci et al. [47] constructed a network system function index based on the total network travel time. Twumasi-Boakye et al. [48] used a construction function based on vehicle travel time in a traffic network as the functional index for the traffic network and assessed the resilience of postdisaster transportation networks based on delay costs and vehicle operating costs. Wu [49] used the total rescue time in a traffic network after an earthquake as a functional index for the emergency phase and the importance of bridges as the basis for order of resilience improvements in the recovery phase. Bocchini et al. [40] and Ishibashi et al. [50] established function index PIs for bridge networks based on the total travel time and total travel distance in traffic networks to evaluate and optimize the resilience of the corresponding road networks. Faturechi [51] studied the resilience of transportation networks using total time travelled as a functional metric. Zhang [52,53] proposed functional index formulas for integrating network topology characteristics, system redundancy characteristics, traffic volume, bridge and road reliability and postdisaster community rescue paths. In the context of major changes in the traffic demand, Liu et al. [54] proposed the weighted average driving speed as a functional indicator for a traffic network. Chang et al. [55] studied the optimization of a post-earthquake bridge network reconstruction scheme based on traffic volume as a functional index. Wang [56] performed post-earthquake functional loss analyses of traffic networks based on the total travel time and service level. Dong et al. [57] comprehensively considered social indicators (downtime and number of fatalities), environmental indicators (energy waste and carbon dioxide emissions) and economic indicators (repair cost, cost of detouring vehicles and costs associated with time loss, environmental loss and life loss) to study the sustainability of highway bridge networks affected by earthquake disasters.

Notably, the functional indicators of bridge networks can generally be divided into three categories: network topology functional indicators, socioeconomic functional indicators and comprehensive functional indicators. The network topology functional indicators encompass the characteristics of the selected bridge network. A bridge network can be transformed into a complex network system by using topology theory, and the characteristics of the spatial network structure can be used to assess the ability of the system to achieve a certain traffic goal. The socioeconomic functional indicators consider the effects of changes in the spatial network structure on actual traffic operations, economic losses and social development under disaster loads. The effects of such changes on actual traffic operations, economic losses and social development are considered. The comprehensive functional indicators combine the advantages of the first two indicator types.

3.2. Resilience Index

Bruneau et al. [33] proposed the concept of the resilience triangle and established a community resilience loss evaluation method based on this concept. The mathematical expression is shown in Equation (1) and reflects a shift from qualitative analysis to quantitative analysis.

$$R_L = \int_{t_\mathrm{r}}^{t_\mathrm{e}} [100 - Q(t)]dt \tag{1}$$

In the above formula, R is the measure of resilience, $Q(t)$ is the actual performance function of the system, t_e is the occurrence time of the disaster and t_r is the completion time of the recovery work after the disaster.

Cimellaro et al. [23] improved the concept of resilience based on the above research results and normalized the resilience value to eliminate the influence of time. The mathematical expression they proposed is shown in Equation (2), and it is associated with the normalized shadow area in Figure 2.

$$R = \frac{\int_{t_r}^{t_e} Q(t)dt}{t_e - t_r} \tag{2}$$

The parameters in the above formula are as defined in Formula (1).

Although the resilience index proposed by Cimellaro eliminates the influence of time to a certain extent, it can only characterize the resilience of the system from the time of a disaster to the time of postdisaster recovery considering only the impacts of the disaster and cannot reflect the resilience of the system at any time under multiple disasters. Therefore, Ouyang [58] further optimized the resilience index proposed by Cimellaro, as shown in Equation (3).

$$R(T) = \frac{\int_0^T Q(t)dt}{\int_0^T Q_P(t)dt} \tag{3}$$

In the above formula, $R(T)$ is the resilience measure related to the objective function at any time T, $Q_P(t)$ is the objective function of the system and $Q(t)$ is the actual function of the system.

However, the above resilience evaluation indicators have shortcomings; that is, in cases in which the normalized shadow area in Figure 2 is the same, it is impossible to examine the resilience differences caused by different initial values of functions, functional losses and recovery paths. Therefore, Liu et al. [54] proposed a resilience loss evaluation method considering the residual ratio of functionality, the robustness of the restoration schedule and the shape of the recovery trajectory, which are the three independent indicators that can be used to describe the corresponding functional curve.

Francis et al. [34] proposed a resilience index for urban road network systems considering the robustness, rapidity, resources and redundancy of the system, as shown in Equation (4).

$$\rho(S_p, F_r, F_d, F_0) = S_p \cdot \frac{F_r}{F_0} \cdot \frac{F_d}{F_0} \tag{4}$$

In the above formula, ρ_i represents the resilience value of the system, S_p is the recovery rate factor, F_r is the new stable value of the system function after the completion of the postdisaster recovery phase, F_d represents the minimum value of the postdisaster system function and F_0 represents the initial stable value of the predisaster system function.

The above resilience indicators are based on the changing characteristics of the functional curve. In addition, relevant scholars have performed research on resilience evaluation indicators considering multiple evaluation factors, such as road network functions and factors related to the economy, society and the environment.

Kilanitis et al. [59] proposed a set of time-varying resilience assessment indicators and cumulative resilience assessment indicators. The time-varying assessment indicators included network functionality, additional traffic costs and the resulting economic, connectivity and environmental losses. The cumulative assessment indicators included structural maintenance costs and traffic costs.

Liu [60] established a multidimensional functional resilience analysis model of bridge networks that integrates the resilience index of the system, the resilience indices of important subsystems and the resilience indices of other sudden disaster events to perform comprehensive analyses of regional bridge networks based on travel distance, travel time and network service level.

Hu [61] fully considered that under snowfall conditions, due to resource limitations, it is impossible to complete road snow removal work in near real time. Therefore, under the premise that the basic operation of a city and the minimum performance requirements of the road network are acceptable to travelers, the comprehensive resilience of the road network was measured from the perspectives of time resilience and performance resilience, and a comprehensive resilience evaluation system was proposed to assess the minimum performance requirements of travelers.

Miu et al. [62] considered five dimensions, namely, community and population, official organizations and management, affordable housing and facilities, the economy and development and the renewable environment and culture, and established the urban resilience evaluation ReCOVER system, which spanned the four stages of rescue, refuge, rebuilding and revival. Then, the resilience of cities was systematically analyzed based on 62 indicators.

Overall, much bridge network resilience-related research is based on the resilience assessment theory developed by Bruneau and Cimellaro [40,59,63–65]. However, other scholars have proposed more comprehensive resilience assessment indicators from their own perspectives. At present, the academic community does not have a generally accepted, accurate and complete definition of resilience or a corresponding assessment indicator system. Therefore, further research by scholars is needed in the future.

4. Research Progress on Bridge Network Resilience

From the perspective of the three-stage development process of functional curves, research on bridge network resilience should ultimately focus on three points: the long-term performance evolution of bridges in the predisaster stage, the static and dynamic response mechanisms of bridges during disasters and the optimization of decision-making and recovery plans for bridge networks after disasters.

4.1. Long-Term Performance Evolution of Bridges before Disasters

In the normal operation stage before a disaster, a bridge network is subjected to generalized disaster loads, such as bridge scouring, chloride ion-induced erosion, low temperatures in cold regions, freeze–thaw cycles and other harsh environmental factors. These factors affect the durability of bridges, and if they are not managed in a timely manner, they will have a negative impact on the function of bridge networks.

Considering the nonlinear time-varying characteristics of related parameters and their interactions, Shafei et al. [66] evaluated the effects of internal parameters, such as concrete properties and diffusion characteristics, and environmental temperature, relative humidity, carbon dioxide and the chloride ion concentration on changes in the corrosion process through transient thermal analysis; they obtained accurate estimates of the deterioration degree of bridges in the operation stage. Considering the influence of chloride ions on the corrosion of concrete bridges, Akiyama [67], Biondini [68], and Cui [69] performed research on individual concrete bridges and assessed the seismic capacity of the bridge life cycle. Ghosh et al. [70] shifted the focus from a single bridge to a bridge network and used field-measured data to update the deterioration parameters of bridges in the network to accurately estimate bridge fragility. Vishwanath et al. [71] extended their research beyond the mechanical performance of bridges and considered seismic effects and chloride ion effects on bridges throughout the entire bridge life cycle; additionally, the economic losses associated with different damage degrees were considered, and a seismic resilience analysis of reinforced concrete bridges was performed. Alipour et al. [72,73] established a seismic fragility model of bridges considering chloride ion erosion and investigated indicators such as the network flow capacity, travel time and connectivity. Then, they comprehensively analyzed the functional trends and economic loss levels and identified effective reinforcement and maintenance schemes for bridge networks after earthquakes; moreover, the seismic resilience of complex bridge network systems was assessed considering bridge deterioration. With the scour depth during floods as a constant, Dong et al. [74] and Wang et al. [75] simulated scour-induced soil erosion by eliminating springs in scour-affected areas from numerical simulations to study the effect of scour on seismic fragility. Based on the above research, Ren et al. [76] optimized a seismic fragility analysis method for bridges considering bridge deterioration and scouring. In addition, many scholars have considered the effects of climate change on bridge risk or community resilience [77–79]. In particular, considering 31 potential climate change factors that may pose serious threats to bridge performance, Nasr et al. [80] studied the potential effects of climate change on the life cycle of bridges.

Relevant scholars have gradually focused on research on the long-term performance of bridge structures and bridge networks considering climate change and bridge degradation effects. Because the mechanical performance of bridges decreases significantly after a long service time, there is no accurate way to assess the remaining capacity of bridges at the time of disasters. Therefore, research on the long-term performance evolution of bridges before disasters is a prerequisite for solving problems related to bridge network resilience. In addition, research on the performance and resilience of bridge networks in harsh environments, such as those with low temperatures and freeze–thaw cycles in cold regions, is relatively rare. This research gap needs to be filled in the future.

4.2. Static and Dynamic Response Mechanisms of Bridges during Disasters

The disaster occurrence stage is the most serious and complex stage of bridge network function loss. For urban bridge networks, natural disasters such as earthquakes, hurricanes, tsunamis and floods, as well as human-derived accidents such as collisions, explosions, fires and overloads, are often encountered. Determining how to fully constrain the static and dynamic response mechanisms of bridges in cases with a single disaster load, multiple loads at the same time and multiple loads in succession is the core step in this stage.

Huang [81] used an actual ground motion record as the ground motion input based on the OpenSEES calculation platform to perform a nonlinear, finite, element-based dynamic time history analysis of reinforced concrete bridges and systematically studied the seismic hazard level, seismic fragility and seismic risk of reinforced concrete continuous-beam bridges, which is the traditional method for analyzing bridge risk. Karamlou et al. [82] proposed a new probabilistic seismic demand model and seismic fragility analysis method, which eliminated the typical assumption regarding the demand probability distribution in traditional seismic fragility methods and improved the accuracy of seismic fragility analysis, but the computational efficiency was reduced. There are hundreds of bridges in a bridge network. When regional-level disasters occur, the calculation workload is obviously large if fragility analysis is performed for each bridge. To this end, Torbol et al. [83] proposed a fragility optimization method based on real bridge acceleration monitoring data by carrying out the long-term health monitoring of bridges and effectively applied monitoring data in bridge seismic fragility assessments. At present, with the integration of artificial intelligence and civil engineering, relevant scholars have begun to focus on seismic fragility analysis methods based on artificial neural networks and machine learning [84–86] to enhance modelling accuracy and computational efficiency.

Ishibashi et al. [50] proposed a fragility assessment method for bridges influenced by earthquake and tsunami disasters and considered tsunami-prone coastal areas after earthquakes. By using metamodels and stepwise logistic regression with a nonlinear logit function, Kameshwa et al. [87] derived a parameterized fragility function for bridges influenced by earthquake and hurricane disasters. With a multi-Euler domain method based on the fully coupled Lagrange and Euler models, Pan et al. [88] studied the blast resistance of bridges in various explosion scenarios by considering the weight and position of explosives and the effects on bridge structures. Based on numerical simulations of bridge fires with the FDS method, Wei [89] established the spatial temperature field of fires that influenced a pre-stressed concrete box girder bridge. Additionally, the temperature field of the main beam interface was identified, and the mechanical performance of the bridge after the disaster was analyzed in detail. Considering the susceptibility to fire, resistance to extinguishing measures and the exposure during a fire, Li et al. [90] established a bridge fire vulnerability hierarchy evaluation model based on the weighted TOPSIS method. Based on system reliability theory and Bayesian networks, Gehl et al. [91] proposed a multihazard fragility function method. Of course, the premise of performing bridge fragility analyses is that the theoretical model of the load must be obtained. Fereshtehnejad et al. [92] used the kriging method to establish a surrogate model of spatially distributed hurricane hazards. In general, by constructing the relationship between inputs and outputs, hazard intensity measures can be quickly and efficiently estimated. However, due to the high cost of disaster loads, few scholars have developed analytical models of loads and instead focused on the numerical simulations of disasters.

Due to the relatively mature development of performance-based seismic probabilistic risk assessment theory, most of the existing related research focuses on the seismic resilience of bridge networks. However, there is an insufficient understanding of theoretical models of disaster loads, such as hurricane loads, fire loads, and explosion loads, which are often not well understood by the public. Moreover, there have been few studies of bridge hazards and fragility under such loads and multiple loads. This makes it difficult to determine the degree of decline in bridge function at the moment of a disaster. Therefore, assessing the static and dynamic response mechanisms of bridge structures under various loads in detail is the core of resilience evaluations of bridge networks under multihazard loads.

4.3. Optimal Recovery Scheme for Bridge Networks after Disasters

The goal of disaster relief and the long-term recovery of bridge networks after disasters is to optimize all repair schemes considering resource constraints. This optimization problem should be solved with an exhaustive method, but it is obviously not appropriate to apply a method to hundreds of individual bridges in a network. For multiobjective optimization problems, a genetic algorithm is an effective computing tool [93]. For example, Frangopol et al. [94] considered the maximization of the resilience index and the minimization of the cost and used multiobjective genetic algorithms to solve this biobjective optimization problem. Additionally, Zhang [52] proposed two optimization objectives, namely, minimizing the total recovery time and the skew of the recovery trajectory, to measure the network recovery speed and efficiency; a metaheuristic technique, namely, the Nondominated Sorting Genetic Algorithm-II, was used to search the Pareto boundary. Then, the approximate optimal solution of the biobjective optimization problem was obtained for the studied bridge network. Moghtadernejad et al. [95] developed an optimal restoration model by using the discrete particle swarm optimization algorithm. This model can consider constraints and limitations on the available budget, work groups and equipment, different levels and speeds of service recovery for assets in various damage states and changes in traffic flows as restorative interventions are executed.

In addition, the effects of changes in the macrotraffic demand and microtraffic flow trajectories on the recovery process of bridge networks should also be considered. By considering the effects of postdisaster building debris, collapsed trees and downed power poles on the actual driving trajectories of vehicles using bridges, Hou et al. [96] improved the cellular automata method and defined the principle of vehicle lane changes to refine simulations of postdisaster traffic flows. Considering the dynamic characteristics of traffic flows with major disturbances, Lv et al. [97] constructed a day-to-day traffic assignment model to effectively simulate the influence of factors such as traveler behavior inertia, road capacity degradation, the network recovery rate and road network congestion on the traffic flow distribution. Feng et al. [98] studied the performance of a transportation network immediately following an earthquake using an agent-based model. The model accounts for abrupt changes in destination, the irrational behavior of drivers in the chaotic aftermath following a severe earthquake, the unavailability of traffic information and an impaired traffic capacity due to bridge damage and building debris. Cimellaro et al. [99] used the agent-based approach to simulate the evacuation of a crowd after an explosion based on NetLogo. The novelty of this method lies in the integration of people's emotions, irrational behavior and altruism into the evacuation simulation. In addition, fractal theory has gradually been applied for the characterization of the spread of COVID-19 and other disasters with different impacts [100–103], and we can integrate this approach into analyses of postdisaster bridge network performance.

At present, research on the postdisaster recovery phase of bridge networks is focused on achieving a fast recovery to the desired level under limited resource conditions. However, there are still many research assumptions being considered, and research processes have not been sufficiently refined; thus, the research conclusions are difficult to apply in practice. Postdisaster recovery is an important part of bridge network resilience research, and people play a very important role in this stage. Overall, there have been few studies that have considered human behavior and management models. In the future, subjective human behavior should be fully considered when simulating postdisaster bridge network performance and specifying the optimal recovery plan so that the research on bridge network resilience can truly shift from engineering resilience to community resilience.

5. Development Trends and Prospects of Bridge Network Resilience Research

In this section, the literature visualization analysis software CiteSpace [104] is used to assess relevant studies in the field of bridge network resilience since 2010. Through analyses of the annual publication volume, keyword co-occurrence and publication trends over time, considering the current research hotspots, the existing problems at this stage of research are discussed. Then, future research trends are identified to provide references for research in the field of bridge network resilience.

5.1. Analysis of the Annual Publication Volume

The annual publication volume can intuitively reflect the output of research results in the field of bridge network resilience; thus, it is an important indicator that can be used to measure the research trends in this field. Since high-level research results from all over the world are included in the Web of Science database, the literature samples retrieved in this paper were obtained from the Web of Science.

We selected bridge resilience, bridge sustainability, transportation network resilience and transportation network sustainability as search topics to obtain as many relevant papers as possible. Additionally, civil engineering was selected as the subject classification, and the search time span was from 1 January 2010 to 9 December 2022. Through the effective selection and sorting of the search results, 188 journal studies were finally obtained. Figure 3 shows the annual publication volume and trends in bridge network resilience research.

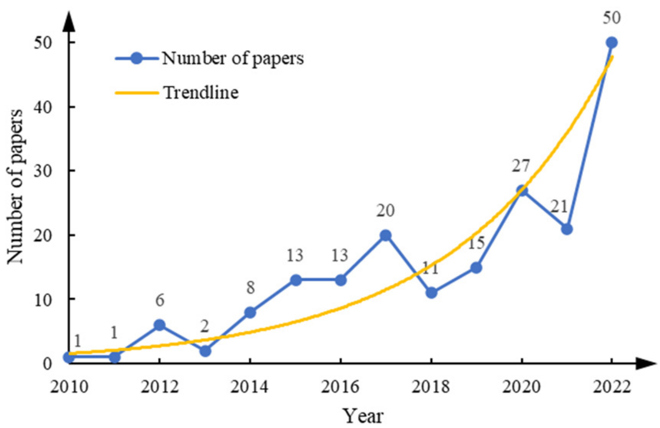

Figure 3. The annual publication volume and trends in bridge network resilience research.

As shown in Figure 3, the period from 2010 to 2014 was the initial stage of exploration in this field, with few researchers involved. From 2015 to 2019, the number of published papers remained at 10 to 20 per year, reflecting a stage of steady growth. From 2020 to the present, as countries around the world began to focus on issues related to urban resilience and develop strong corresponding policy support, more researchers began to perform research on bridge network resilience. This focus on major national strategic needs led to a turning point of growth in the field.

5.2. Keyword Co-Occurrence Analysis

Keywords are the major topics covered in a paper and are key indicators that reflect the central ideas of the research. The keyword frequency represents the attention degree of a node in a certain field, and keyword centrality represents the mediation and influence degrees of a node in a certain field. The parameters in the CiteSpace software were set based on literature samples, and a keyword co-occurrence network was constructed for bridge network resilience research. As shown in Figure 4, the network consists of 624 nodes and 2762 links. The larger a node is, the higher the frequency of the corresponding keyword. In addition, the statistical results for high-frequency and high-centrality keywords are shown in Tables 2 and 3, respectively.

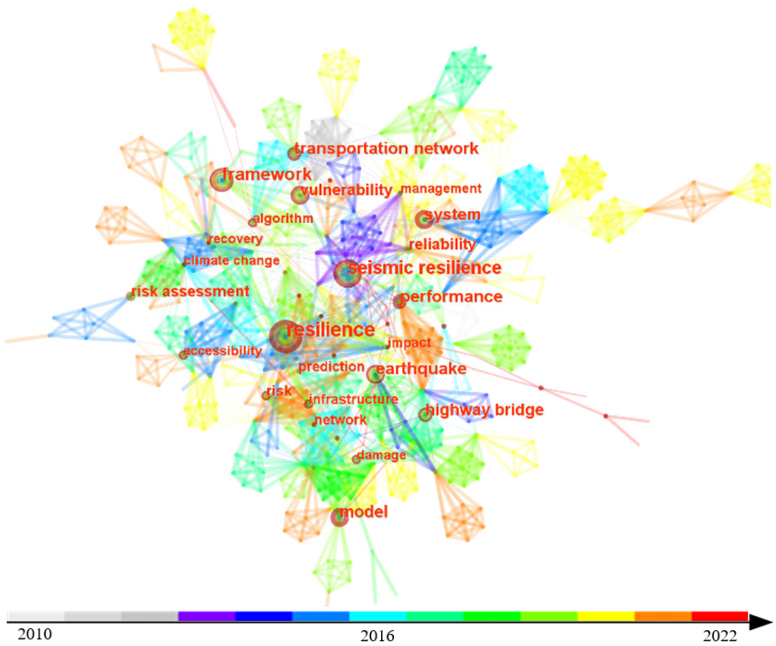

Figure 4. Keyword co-occurrence network.

It can be concluded from Table 2 that keywords with high co-occurrence frequencies are resilience, seismic resilience, framework, performance and transportation network. These keywords fully reflect the current research status of bridge network resilience, spanning from research on the mechanical performance of bridges under disaster loads to studies of the performance of transportation networks. However, at present, most keywords are related to seismic resilience, and few studies of bridge network resilience have focused on other disaster types.

Table 3 shows that keywords such as impact, climate change, behaviour, algorithm and system correspond to high centrality values, indicating that in today's macrocontext of climate change, in studies of resilience, focus is placed on the overall effects of disasters or shocks on the bridge network system, not just a single bridge. In addition, solving complex system problems requires a large number of computations. In today's era of artificial intelligence, algorithms are a good choice for addressing this issue.

Table 2. High-frequency keyword statistics.

Sequence Number	Keywords	Count	Sequence Number	Keywords	Count
1	resilience	42	16	impact	12
2	seismic resilience	31	17	recovery	12
3	framework	26	18	climate change	11
4	performance	24	19	network	11
5	transportation network	24	20	prediction	11
6	earthquake	23	21	management	10
7	model	22	22	accessibility	10
8	system	21	23	damage	10
9	highway bridge	18	24	design	9
10	vulnerability	17	25	optimization	9
11	reliability	14	26	robustness	9
12	risk assessment	14	27	bridge	8
13	risk	13	28	road network	8
14	algorithm	13	29	seismic fragility	8
15	infrastructure	12	30	sustainability and resilience	8

Table 3. Keyword centrality statistics.

Sequence Number	Keywords	Centrality	Sequence Number	Keywords	Centrality
1	impact	0.27	16	seismic resilience	0.08
2	climate change	0.24	17	transportation network	0.08
3	behaviour	0.24	18	earthquake	0.07
4	algorithm	0.24	19	management	0.07
5	system	0.22	20	design	0.07
6	performance	0.15	21	functionality	0.07
7	restoration	0.13	22	deck	0.07
8	risk	0.11	23	design problem	0.07
9	event	0.11	24	reliability	0.07
10	curve	0.10	25	reinforced concrete bridge	0.06
11	formulation	0.10	26	failure	0.06
12	recovery	0.10	27	seismic hazard	0.06
13	bridge	0.09	28	repair	0.06
14	extreme event	0.09	29	simulation	0.06
15	retrofit	0.09	30	hazard	0.06

A comparison of Tables 2 and 3 suggests that the frequency and centrality of keywords differ among the rankings, indicating that the research hotspots of bridge network resilience in the field of civil engineering are not consistently clear over time. Among them, the keywords that rank high in both frequency and centrality include performance, system, risk and climate change, which suggests that they are popular topics in the field of bridge network resilience. Additionally, these keywords reflect the reasons for, subjects in and analysis methods applied for bridge network resilience research. The keywords algorithm, behaviour, event and restoration display relatively high centrality, indicating that the intermediary effect of these keywords is obvious. Although their frequencies are relatively low, their intermediary role suggests that artificial intelligence-based postdisaster performance simulation and restoration for bridge networks is the basis for the development of resilient cities and research in the field.

The cluster labels of keywords were extracted, and the keyword clusters for bridge network resilience research were illustrated. The smaller the cluster label number is, the more keywords there are in the category, and the stronger the correlation among keywords. The cluster labels of bridge network resilience research keywords were sorted from small to large as follows: seismic assessment, community resilience, climate change, bridge resilience, link and seismic fragility.

5.3. Keyword Time Series Evolution Analysis

To mine the period of popularity of a certain keyword, the Kleinberg algorithm embedded in CiteSpace software was used for the time series evolution analysis. The results are shown in Table 4. The higher the keyword strength value, the more attention it receives in the considered time interval. The emergent keywords can change within a certain period of time, reflecting the research trend in the corresponding period. And the red part in the horizontal line is the time range of the keyword emergence, based on which the frontier topic at this stage can be determined. In the initial period, scholars explored the seismic resilience of bridge networks based on the seismic fragility and structural reliability of bridges. Later, based on the above research, the reliability of complex bridge network systems was used to analyze regional bridge network resilience from multiple dimensions. Currently, bridge network resilience research involves network deterioration in the case of multidisaster loads, and the results can help solve bridge network resilience and sustainability problems throughout the life cycle of bridges.

Table 4. Emergent keyword statistics.

Emergent Keywords	Strength	Begin	End	Year (2020–2022)
seismic resilience	1.94	2011	2014	
reliability	1.57	2013	2016	
capacity	1.72	2014	2016	
network reliability	1.40	2015	2017	
system reliability	2.02	2016	2017	
structural safety and reliability	1.63	2016	2017	
load	1.41	2016	2019	
flow	1.52	2018	2019	
deterioration	1.70	2019	2019	
damage	2.23	2020	2020	

5.4. Outlook for Future Development

Based on the results of the keyword co-occurrence and time series evolution analyses of the bridge network resilience literature, combined with the research status of bridge network resilience in civil engineering, the potential development prospects in this field are described.

(1) Focus should be placed on improving the structural health monitoring of bridges in intelligent assessments of resilience. It is ideal to establish bridge models based on numerical simulations and obtain the response of a structure by applying a disaster load. In the actual operation stage, bridges are affected by factors such as material ageing, environmental corrosion and increased load strength, resulting in bridges reaching different damage states. In regional bridge networks, the service time, structural form, load and environment of bridges are generally similar. Therefore, in the structural health monitoring of bridges, various types of sensors can be deployed to obtain a representation of the actual state of the bridge, and response data can be collected. On this basis, mechanical performance evolution models of bridges monitored in clusters can be established considering the spatiotemporal relationships among bridge damage and other factors during actual disasters. This approach could effectively combine big data and intelligent assessments of bridge network resilience.

(2) Research on the evolution of bridge performance under multihazard actions should be further promoted. When a disaster occurs, it is often accompanied by other disasters, which can occur in sequence. The cumulative damage caused by this series of loads to bridges cannot be ignored. For example, tsunamis can be caused by earthquakes, floods can be caused by typhoons and explosions can be caused by vehicles crashing into

bridges, leading to fires. In addition, for large-scale disaster loads, both uncertainty and spatiality should be considered. Previous studies have focused on the seismic resilience of bridge networks, but there is a lack of research on other disasters. Therefore, determining how to accurately establish theories and numerical models for various disaster loads and identifying the evolution mechanism of bridge performance under the coupled actions of multiple disasters are difficult problems that need to be solved in the future.

(3) Bridge network resilience assessments should be enhanced throughout the whole bridge life cycle. Bridges are influenced by different processes throughout their service period, including harsh long-term environmental effects and short-term natural disasters or accidents. Notably, the occurrence time of short-term disaster loads is uncertain, thus influencing the long-term resilience of bridge networks. Therefore, in future work, the effects of all possible disasters on the resilience of bridge networks can be considered in detail during the designed life of the bridge, and a method for assessing and improving the resilience of bridge networks throughout the bridge life cycle should be established to provide guidance for maintenance, reinforcement and disaster preparedness decisions. Additionally, with this approach, future urban bridge network planning and construction can be enhanced.

6. Conclusions

In this paper, the concept of resilience is summarized, and the functional and resilience indicators used for bridge networks are described. Moreover, the long-term performance evolution of bridges is explored, and the static and dynamic response mechanisms of bridges under disaster loads are described. In addition, research on the optimal restoration scheme for bridge networks in the postdisaster phase is summarized, and through the visualization analysis software CiteSpace, the development trend of bridge network resilience research is identified. Finally, future development prospects are proposed. The following conclusions are obtained.

(1) With global climate change, the acceleration of urbanization and continuous improvements in social and economic levels, the international community has gradually begun to focus on disaster prevention and mitigation and the postdisaster relief and recovery of cities influenced by disasters. In the past decade, an increasing number of scholars from all over the world have started to research the resilience of urban bridge networks. However, the concept of bridge network resilience is still unclear, and there is no unified standard for the selection of functional indicators and resilience assessment methods.

(2) Bridge network resilience problems can be addressed by establishing refined descriptions and accurate evaluations of bridge network functions and their variations over time in the context of disasters. Thus, it is necessary to perform research on the mechanical performance of bridge structures, the operational performance of transportation networks and the impact on the urban economy and society. This is a complex multidisciplinary problem involving civil engineering, traffic engineering, technology, economics, sociology and other disciplines.

(3) For large bridge networks containing hundreds of bridges, traditional methods of resilience evaluation will yield low-accuracy results and are generally inefficient. In the future, advanced technologies and methods from data science and machine learning should be used to establish bridge fragility models considering multiple disasters, enhance the intelligent recovery of complex networks after disasters and effectively integrate bridge structural health monitoring data and bridge network resilience research.

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