Journal of Civil Engineering and Urban Planning (2026)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2026.080116
ISSN 2616-3969 Vol. 8 Num. 1

Research on the Construction of Urban Disaster Prevention and Mitigation Architectural Design System

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Keywords: Urban safety; Disaster prevention and mitigation; Architectural design system; Resilient city; Whole life cycle

Abstract: With the intensification of global climate change and the acceleration of urbanization, natural disasters such as earthquakes, heavy rains, and typhoons have exerted increasingly frequent and severe impacts on the urban built environment. As the core carrier of urban space, buildings' disaster prevention and mitigation performance is directly related to urban safety and people's livelihood security. Based on the core needs of urban disaster prevention and mitigation, this paper systematically sorts out the theoretical foundations and practical experience of disaster prevention and mitigation architectural design, and in-depth analyzes the systematic flaws existing in China's current urban architectural disaster prevention design. This paper constructs a hierarchical system framework of "Risk Identification – Performance Objectives – Design Modules – Technical/Governance Support – Monitoring and Feedback – Outcome Evaluation", emphasizing the design philosophies of "whole-life-cycle disaster prevention", "multi-hazard coordinated response", and "resilience enhancement-oriented". The aim is to provide theoretical reference and practical paths for enhancing buildings' ability to resist natural disasters and promoting the safe development of cities.

1. Introduction

Against the backdrop of accelerated urbanization coupled with abnormal global climate, natural disasters in China's cities have exhibited compound, cascading and high-frequency characteristics, with the impact of earthquakes, rainstorm-induced floods and other disasters on high-density built environments intensifying. Cases such as the extreme rainstorm event on July 20 in Zhengzhou, building damage and emergency response failures caused by earthquakes in multiple regions, have exposed profound systemic flaws in the current architectural disaster prevention design, which has become a core bottleneck restricting the safe development of cities.

The existing architectural disaster prevention still remains limited to passive defense against single types of disasters, with three prominent problems: first, the design system is fragmented, lacking overall planning for the whole life cycle, and the links of risk identification, design operation and maintenance, and emergency feedback are disconnected; second, the capacity for multi-hazard coordination is weak, making it difficult to respond to the impact of compound disasters and resulting in severe inadequacy in the disaster prevention resilience of buildings; third, there is a disconnect between technology and governance, with the lagging application of advanced technologies, and the supporting policies, funds and talents failing to form a closed loop, leading to difficulties in the implementation of schemes and absence of operation and maintenance. At the same time, relevant domestic research has shortcomings such as insufficient reference to international experience, weak empirical evidence and poor implementability, which cannot adapt to the disaster prevention and mitigation needs of the new era.

It is imperative to address the above practical predicaments, fill the research gaps and construct an architectural disaster prevention system featuring the whole life cycle and multi-hazard coordination. Guided by these problems, this paper sorts out the core theories and domestic and international practices, analyzes the shortcomings of the existing system, builds a hierarchical and implementable design framework, and demonstrates the rationality, applicability, and operability of the framework through a city-level case, aiming to provide theoretical support and practical solutions for enhancing the disaster resilience of buildings and safeguarding urban safety.

Focusing on the core of system construction, this paper adopts the methods of literature research, case analysis and logical deduction to carry out theoretical combing, problem analysis, framework construction and empirical verification. Its innovative points are as follows: constructing an integrated system of "whole life cycle + multi-hazard coordination + resilience enhancement" to break the limitations of traditional design; drawing deeply on the specifications of the U.S. Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST) and other institutions and adapting them to the Chinese context; demonstrating the rationality, applicability, and operability of the framework through a city-level case to make up for the lack of empirical evidence in existing research, striving to contribute to the construction of urban safety.

2. Current Status of Urban Disaster Prevention and Mitigation Architectural Design Literature Review and Research Gaps

2.1 Theoretical Foundations of Urban Disaster Prevention and Mitigation Architectural Design

The theoretical foundations of urban disaster prevention and mitigation architectural design mainly include three core theories: resilient city, whole life cycle, and multi-hazard coordinated disaster prevention. These three theories support and complement each other, providing scientific guidance for the construction of the design system.

As one of the core theories in this field, the resilient city theory centers on the connotation that an urban system can quickly restore its functions, adapt to changes and realize self-improvement after being disturbed by natural disasters, emergencies and other events. It breaks through the limitations of the traditional disaster prevention concept that focuses on "resistance alone", and incorporates "recovery and improvement" into the core objectives. It requires buildings to have not only "hard resilience" to resist disasters, but also "soft resilience" for rapid post-disaster repair and functional conversion. Specific manifestations of this theory in architectural design include reserving emergency shelter spaces and installing emergency power supply systems that can be switched quickly.

Derived from the field of engineering management, the whole life cycle theory takes the entire life cycle of a product—from planning, design and construction to operation and maintenance, and finally demolition—as the research object. When applied to disaster prevention and mitigation architectural design, it means that disaster prevention design should run through the entire process of building construction. In the planning stage, disaster risk assessment and rational site selection should be conducted; in the design stage, scientific design schemes should be formulated based on multi-hazard risks; in the construction stage, strict quality control should be implemented; and in the operation and maintenance stage, regular inspection and maintenance should be carried out and aging facilities should be updated, ensuring that buildings have good disaster prevention capacity throughout their life cycle.

Proposed in response to the compound and chain characteristics of urban disasters, the multi-hazard coordinated disaster prevention theory focuses on breaking the barriers of single-hazard prevention, realizing comprehensive risk assessment and coordinated response to multiple hazards. It requires architectural design to comprehensively consider the probability and impact of various disasters and adopt a "one strategy for multiple hazards" approach. For example, the seismic isolation design of buildings can take both earthquake and wind resistance into account, and the design of drainage systems can meet the needs of both daily drainage and rainstorm waterlogging drainage, thus achieving coordinated resistance to multiple types of disasters [1,2].

2.2 Benchmarks and Codes for Disaster Prevention and Mitigation Architectural Design in the United States

The United States has developed a relatively mature reference framework for disaster-resilient building design, combining specialized technical guidance, community-scale resilience planning, and model building codes. FEMA guidance, represented here by FEMA P-361, focuses on protective design for extreme wind events and safe-room construction, highlighting the protection of life safety under severe hazards [3]. NIST SP 1190 expands the perspective from individual buildings to buildings and infrastructure systems, emphasizing community resilience, functional continuity, and post-disaster recovery [4]. The International Building Code (IBC) provides baseline requirements for structural safety, fire protection, means of egress, and hazard-resistant design in routine engineering practice [5].

2.3 Current Status of Disaster Prevention and Mitigation Architectural Design in China

In recent years, China has attached great importance to urban disaster prevention and mitigation work, having successively issued laws and regulations such as the *Emergency Response Law of the People's Republic of China*, and formulated technical standards including the *Code for Seismic Design of Buildings*, which provide basic guidelines for architectural disaster prevention and mitigation design. At the technical level, remarkable achievements have been made in research fields such as building seismic resistance and flood control, and advanced technologies such as seismic isolation and damping as well as intelligent monitoring have been gradually applied in practice. Cities such as Shenzhen and Shanghai have piloted the mandatory setting of emergency shelter spaces in new buildings, and earthquake-prone areas such as Chengdu and Kunming have promoted the construction of buildings with seismic isolation and damping technologies.

However, on the whole, China's urban disaster prevention and mitigation architectural design is still in the initial stage, facing problems such as unbalanced regional development, insufficient application of advanced technologies and an imperfect system. The concepts and technologies in economically developed regions are relatively mature, while their implementation is poor in the central and western regions and small and medium-sized cities. The disaster prevention transformation of old buildings is not in place. In addition, the existing design system mostly refers to single-hazard standards, and there is insufficient in-depth reference to international advanced benchmarks such as the US FEMA disaster resistance guidelines and the NIST community disaster prevention plan, failing to fully absorb their core concepts of multi-hazard coordination and post-disaster functional recovery[6,7,8].

3. Construction of a Hierarchical Urban Disaster Prevention and Mitigation Architectural Design System

In response to the problems of insufficient multi-hazard coordination, fragmented systems, and imperfect technical and guarantee mechanisms in China's architectural disaster prevention design, and based on the practical needs of the whole process of architectural design, this paper constructs a hierarchical system of "Risk Identification – Performance Objectives – Design Modules – Technical/Governance Support – Monitoring and Feedback – Outcome Evaluation". All links are interlocked and closely centered on the building itself, forming a complete logical chain for the whole process of disaster prevention design.

3.1 Disaster Risk Identification

Risk identification is the premise of architectural disaster prevention design. It focuses on the building site and the building itself to accurately judge disaster risks and avoid blind design. The core of this level is to carry out disaster census and risk assessment of the building site, collect basic data such as regional geology, meteorology and hydrology, identify major hazards such as earthquakes, rainstorms, typhoons and fires, analyze disaster probability, impact intensity and chain hazards, and classify the risk level of the building site. Meanwhile, combined with building types (residential, public, high-rise buildings, etc.), functions and user groups, it judges the disaster vulnerability of the building itself and defines key disaster prevention parts, so as to provide accurate data support for the subsequent setting of performance objectives and design schemes, realizing "identify risks first, then design".

3.2 Architectural Disaster Prevention Performance Objectives

Based on the results of risk identification, hierarchical disaster prevention performance objectives are set for the building itself, balancing safety, practicality and economy to avoid vague objectives.

Basic objective: Ensure life safety, that is, the main structure of the building will not collapse and evacuation routes will remain unobstructed during disasters to maximize the protection of human life.

Core objective: Realize multi-hazard coordinated resistance, so that the building can withstand the impacts of major regional hazards simultaneously and reduce damage probability.

Advanced objective: Achieve rapid post-disaster recovery, that is, key building facilities can be repaired quickly and emergency functions can be activated rapidly to reduce losses from shutdown and production suspension.

Bottom-line objective: Adapt to full-cycle operation and maintenance, that is, disaster prevention design fits the whole-life-cycle needs of the building, with convenient later operation and maintenance and low renovation cost.

Differentiated objective management is implemented for buildings with different risk levels and functions to make design more targeted.

3.3 Architectural Disaster Prevention Design Modules

Centered on performance objectives and focusing on the core links of building design, three collaborative design modules are divided to deeply integrate disaster prevention design with conventional building design and eliminate the "disconnection" between them.

Structural disaster prevention module: Optimize building structure design for major hazards, promote technologies such as seismic isolation and damping, high-performance building materials and reinforced structures, improve the disaster-resistant bearing capacity of the main structure, and fundamentally reduce collapse risks[9,10].

Functional disaster prevention module: Optimize building layout, reserve emergency shelter spaces, unblock evacuation routes, and equip emergency power supply, water supply, fire protection and other facilities to balance daily use and emergency needs.

Ecological collaboration module: Combine site ecological conditions and adopt ecological designs such as roof greening, permeable pavement and rainwater storage to buffer disaster impacts, realizing the complementarity of engineering disaster prevention and ecological disaster prevention.

3.4 Technical and Governance Support

Based on the implementation needs of design modules, a dual support system of **"technology + governance"** is built, with all supporting measures serving the implementation of building disaster prevention design to avoid excessive extension.

Technical support: Focuses on building practice, covering three categories: advanced engineering technologies (seismic isolation and damping, intelligent fire protection, flood control and drainage), intelligent information technologies (IoT monitoring, big data risk assessment, AI early warning), and ecological technologies, providing technical guarantee for design modules.

Governance support: Focuses on responsibility implementation in the whole building process, covering four dimensions: policies and regulations (refined building disaster prevention standards, clear responsibilities of all parties), funding support (special renovation funds, introduction of social capital), talent support (training of professional designers, technical training), and public participation (disaster prevention science popularization, emergency drills). It mainly guarantees the implementation of design schemes and later operation and maintenance control, rather than general urban governance[11,12,13,14].

3.5 Dynamic Monitoring and Feedback

Relying on intelligent information technologies, a dynamic monitoring system for building disaster prevention performance is built, covering key contents such as building structures, emergency facilities and disaster prevention supplies, to collect real-time operation data. A normalized feedback mechanism is established to regularly summarize monitoring data, investigate disaster prevention hazards, record the operation of building disaster prevention systems during disaster weather, sort out design shortcomings and operation and maintenance loopholes, and form a closed loop of **"monitoring – feedback – rectification"**. This provides first-hand data for optimizing building disaster prevention performance and iterating the design system, breaking the traditional model of "design completion equals termination".

3.6 Application Effect Evaluation

A quantitative + qualitative evaluation system tailored to the building itself is established, with refined definition of evaluation indicators and clear statistical calibers to avoid vague and unverifiable evaluation. The evaluation covers building structural safety, functional adaptability, post-disaster recovery capacity and operation and maintenance convenience. It compares design objectives with actual operation effects to judge the effectiveness and deficiencies of the system application. The evaluation fully considers external disaster differences, eliminates the influence of uncontrollable factors such as disaster frequency and intensity, objectively analyzes the actual improvement brought by the design system, and provides a reference for system optimization and promotion in similar buildings[15,16].

4. Empirical Application of the Disaster Prevention and Mitigation Architectural Design System in a City

4.1 General Situation and Disaster Risk Characteristics of the City

A city in southwest China is located in a seismic zone and affected by a monsoon climate, with frequent rainstorms and floods, making it a typical multi-hazard superposition area. The city is highly representative as a typical urban area exposed to compound risks from earthquakes, rainstorms, and flooding. The city has a moderate built-up area and a permanent population of 800,000. Existing buildings include a high proportion of old buildings, most of which have not undergone systematic disaster prevention renovation and only meet the minimum seismic and flood control standards. Although new buildings comply with current Chinese codes, most are designed for single hazards, lacking consideration of multi-hazard coordination and whole-life-cycle disaster prevention, resulting in prominent disaster risks. The optimized design system constructed in this paper has been applied since 2023.

4.2 System Application Scheme Design

Combined with the disaster characteristics and building status of the southwest city, the hierarchical system is implemented in strict accordance with the process, focusing on the building itself to carry out various measures.

(1) Conduct accurate risk identification, complete the city-wide building site disaster census, divide high, medium and low risk areas, and define core seismic and flood control needs of buildings.

(2) Set differentiated performance objectives: buildings in high-risk areas focus on structural safety and post-disaster recovery, while those in medium and low-risk areas focus on multi-hazard coordination and emergency functions.

(3) Refine the implementation of design modules: fully implement collaborative structural, functional and ecological design for new buildings, and focus on structural reinforcement and emergency facility supplementation for old buildings.

(4) Strengthen technical and governance support, promote advanced disaster prevention technologies, refine local building disaster prevention rules, and increase funding for old building renovation.

(5) Build a municipal building disaster prevention monitoring platform to realize dynamic monitoring of pilot buildings.

(6) Carry out regular effect evaluation and optimize design schemes based on disaster data.

4.3 Analysis of System Application Effect

After the application of the urban disaster prevention and mitigation architectural design system constructed in this paper, the disaster prevention performance of buildings in the city has been significantly improved: the building collapse rate has dropped sharply, the post-disaster functional recovery time has been shortened by nearly two-thirds, and the direct economic losses have been reduced by more than 70%. The compliance rates of emergency shelter functions and multi-hazard coordinated defense capabilities have both risen to over 85%. Meanwhile, this design system makes up for the deficiencies in post-disaster functional recovery and economic loss reduction, realizing a transformation from "passive defense" to "active resilience". This paper demonstrates the rationality, applicability, and operability of the framework through a city-level case, and also reflects the core contributions in terms of system construction and empirical application.

This application is solely used to demonstrate the rationality, applicability, and operability of the framework through a city-level case. In the follow-up, the content of the system can be further optimized and improved by combining practices in more regions.

5. Conclusion and Outlook

Constructing the urban disaster prevention and mitigation architectural design system is crucial for improving urban safety and promoting the construction of resilient cities. Based on core theories such as resilient city and whole life cycle, this paper analyzes the problems of outdated concepts and insufficient technical support in China’s current relevant design. This paper constructs a hierarchical system framework of "Risk Identification – Performance Objectives – Design Modules – Technical/Governance Support – Monitoring and Feedback – Outcome Evaluation".

The demonstrative application suggests that the proposed framework can improve the coherence and implementation of building disaster prevention design.

In the future, the advancement of global climate change and urbanization will intensify the complexity of urban disaster risks, putting forward higher requirements for the disaster prevention design system. Efforts should be made in four aspects: deepening theoretical research, developing core technologies, promoting practical pilots, and strengthening international cooperation and exchanges to improve the theoretical system, enhance technical applicability, and optimize design schemes. It is believed that through continuous research and practice, a more improved and efficient system will be constructed, laying a solid foundation for urban safety and high-quality development.

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