Analysis of Safety and Durability in Municipal Bridge Design

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Abstract: Focusing on the core role of municipal bridges in urban transportation, this paper systematically analyzes the importance of safety and durability for traffic safety, public interest, and the stability of urban transportation systems. It proposes pathways for enhancing safety from three aspects: optimizing structural stress, improving protective facilities, and strengthening emergency evacuation. It also constructs a system for reinforcing durability from three aspects: selecting optimal corrosion-resistant materials, designing for drainage and impermeability, and reserving maintenance space. The research results aim to demonstrate that targeted design strategies can effectively reduce bridge safety risks and extend service life, providing a practical and professional reference framework for municipal bridge design, thereby helping to enhance the bridge's whole-life-cycle service capability.

1. Introduction

As critical links in urban transportation networks, the operational state of municipal bridges directly affects citizen travel safety, the efficiency of public resource utilization, and the smooth conduct of urban economic activities. Currently, some bridges, due to insufficient consideration of safety redundancy and inadequate durability protection measures during the design stage, gradually develop issues such as structural cracking and performance degradation under long-term load and environmental erosion. This not only increases maintenance costs but also poses potential threats to traffic operation and public safety. In this context, in-depth analysis of the core points of safety and durability in municipal bridge design, and teasing out scientific and effective design strategies, have become important tasks for solving bridge operation pain points and ensuring the sustainable development of urban transportation.

2 Importance of Safety and Durability in Municipal Bridge Design

2.1 Ensuring Traffic Safety and Public Interest

From a safety perspective, municipal bridges daily bear diverse traffic loads, including dynamic impacts from heavy trucks and concentrated loads during peak pedestrian flow. If the structural design lacks sufficient safety redundancy, with inadequate bending strength of main girders or insufficient seismic performance of bearings, it can easily lead to hazards such as girder cracking and bearing displacement, potentially causing structural collapse and casualties in severe cases. Safety design must cover detailed protection; insufficient anti-slip performance of the deck or weak anti-collision capability of guardrails increases the probability of accidents like vehicle skidding and pedestrian falls, directly threatening user safety [1]. From a durability perspective, if bridges suffer from poor material corrosion resistance or defective impermeability design, leading to accelerated steel corrosion and concrete carbonation, their service life can be significantly shortened. A bridge designed for 50 years might require major repairs after only 20 years. Frequent repairs not only occupy substantial public funds but also affect citizens' daily travel due to traffic control during maintenance, reducing public service efficiency. Bridges with insufficient durability, if not

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maintained timely, may become "dangerous bridges" due to structural performance degradation, requiring long-term traffic restrictions or closure, forcing renewed public investment in new bridges, causing resource waste and further damaging public interest.

2.2 Maintaining Stable Operation of the Urban Transportation System

Regarding the impact of safety on the transportation system, sudden bridge failures due to design safety defects, such as damaged piers from impact or fallen expansion joints, can directly lead to bridge closure. As some bridges in urban transportation networks are often the only passage between regions, once interrupted, it can cause traffic congestion upstream and downstream, even triggering chain reactions, paralyzing the surrounding road network, and affecting key economic and social activities like logistics and commuting. Bridges with unaddressed safety hazards may experience safety accidents induced by extreme weather, further increasing the emergency response pressure on the transportation system [2]. Analyzing the impact of durability on the transportation system, bridges with insufficient durability require regular maintenance and reinforcement. During maintenance, measures like load limitation, one-way traffic, or even full closure are usually necessary. This alters original traffic flow paths, causing a surge in traffic volume on detour routes and reducing traffic efficiency. If durability issues are severe, requiring long-term closure for repair, "breakpoints" can appear in the urban transportation network, disrupting regional traffic links. Interruption of bridges between industrial parks and logistics hubs can delay raw material transport and product delivery cycles for enterprises, directly impacting regional economic development.

3. Strategies for Enhancing Safety in Municipal Bridge Design

3.1 Optimizing Structural Stress Design

Conduct refined load calculation: Move beyond traditional static load analysis limitations. Establish a dynamic load database incorporating traffic flow data from the bridge's location, geological hazard probability, and temperature stress variation patterns. Use finite element analysis software for 3D stress simulation of key components like main girders, bearings, and piers, focusing on areas prone to stress concentration such as mid-span and near supports, ensuring component cross-sectional dimensions and material strength match stress requirements [3]. Strengthen structural system redundancy design: Add shear keys and energy dissipation devices at connections between main girders and piers. When the stress on a single component exceeds the threshold, the redundant structure can quickly share the load, avoiding local failure leading to overall collapse. Simultaneously, for long-span bridges, use a combined system of continuous girders and rigid frames, distributing bending moments by adjusting bearing stiffness, reducing the stress burden on larger span sections [4]. Implement whole-life-cycle stress monitoring reserved design: Pre-embed optical fiber sensors and strain gauges inside key components. Clearly specify sensor installation locations, data transmission paths, and protective measures during design, enabling real-time monitoring of structural stress changes during operation. When monitoring data exceeds early warning values, maintenance and reinforcement plans can be initiated promptly, avoiding the accumulation of stress damage leading to safety accidents.

3.2 Improving Protective Facility Design

Optimize deck traffic protection facilities: For separating motorized and non-motorized lanes, use wave-shaped anti-collision guardrails over 1.2m high, with concrete bases added at the bottom to enhance impact resistance. Use mortise-and-tenon joints at guardrail connections to avoid sharp fragments from breakage upon collision. Set up protective railings at least 0.8m high at pedestrian walkway edges, with railing spacing controlled within 11cm to prevent children from climbing and falling. Install anti-slip rubber strips on the inside of railings to prevent direct impact with hard railings if pedestrians slip. Design deck drainage outlets as grates with apertures not exceeding 2cm to prevent debris blockage causing water accumulation. Lay 2m wide anti-slip asphalt around drainage outlets to reduce vehicle skidding risk in rain [5]. Strengthen external protection of bridge structure: Use wrapping-type fenders for bridge piers. Select high-elasticity polyurethane as fender material with a thickness not less than 50cm. Install steel structural skeletons inside the fenders to enhance impact stiffness. When ships or floating objects impact the pier, the fender can absorb impact energy through deformation, reducing pier damage. For the bottom of girders in the superstructure, apply anti-corrosion coatings and install metal protective covers. Leave a 5cm ventilation gap between the cover and the girder to prevent direct contact with rainwater and corrosive gases. Regularly inspect the integrity of protective covers and replace damaged parts promptly.

3.3 Strengthening Emergency Evacuation Design

Develop scenario-based emergency evacuation plans: Conduct evacuation simulation analysis for different accident types. Taking fire accidents as an example, consider smoke spread speed and temperature distribution. Set up fire barriers every 50m on the deck, using flame-retardant materials with a width not less than 3m. Install fire hydrants and extinguishers near the barriers, with hydrant spacing not exceeding 120m. For collapse accidents, predict potential collapse ranges and set up emergency evacuation channels on both sides of the bridge, with a width not less than 2.5m, constructed with reinforced concrete for structural stability. Set gentle slopes at the connection between the channel and the deck to facilitate evacuation for people with limited mobility [6]. Optimize emergency guidance and signage systems: Install emergency evacuation signs every 20m on the deck. Use self-luminous materials for the signs so they remain clearly visible during power outages. The signs should clearly indicate the current location, distance to the nearest exit, and evacuation route map. Set up emergency broadcast systems at both ends of the bridge, with coverage encompassing the entire deck. In case of an accident, real-time information and evacuation instructions can be broadcast. Also, install emergency call buttons on the deck with spacing not exceeding 100m, allowing people to press for help directly in emergencies.

4. Strategies for Enhancing Durability in Municipal Bridge Design

4.1 Selecting Optimal Corrosion-Resistant Materials

Conduct material corrosion risk assessment: Classify corrosion risk levels (high, medium, low) based on the climatic characteristics, environmental media, and component stress state of the bridge's location. Treat pier columns in coastal areas as high corrosion risk, and decks in inland dry areas as medium to low risk [7]. Select materials precisely by component: For underground or underwater components with high corrosion risk, such as piers and foundations, use weather-resistant steel with additional epoxy coal tar pitch coating, controlling coating thickness between 0.3-0.5mm. Also, apply hot-dip galvanizing on the steel surface with a zinc layer thickness not less than 85μm to enhance resistance to salt spray corrosion. For deck pavement layers, use modified asphalt concrete with asphalt penetration controlled at 40-60 and softening point not lower than 60°C. Incorporate 3%-5% anti-aging agents to improve resistance to UV and high-temperature aging. For connecting components like bearings, use a combination of polytetrafluoroethylene (PTFE) sliding plates and stainless steel plates, with the sliding plate surface roughness $Ra \leq 0.8\mu m$ to reduce friction wear and chemical corrosion.

4.2 Optimizing Drainage and Impermeability Design

Strengthen deck drainage design: Set deck cross slope at 2%-3% and longitudinal slope not less than 0.3% to ensure rainwater quickly collects towards the sides. Set drainage outlets every 10-15m along the deck edge, using a lateral layout to avoid direct water impact on girders. Install filters inside outlets to prevent debris blockage. Use UPVC material for connected drainage pipes with a diameter not less than 150mm and a pipe slope not less than 5% to ensure smooth drainage. For deck expansion joints, use a combination of rubber waterstops and stainless steel cover plates for impermeability. The waterstop width should be not less than 30cm, and interface agent should be applied on the contact surface with concrete to enhance bonding and prevent rainwater from seeping into the girder through the joints [8]. Improve component impermeability measures: Inside bridge box girders, set longitudinal drainage grooves at the junction of the top slab and web, with groove width not less than 10cm and depth not less than 5cm. Set vertical drain pipes every 20m to discharge condensation or seepage water from inside the box girder. For the connection between piers and foundations, use water-expanding sealant strips for encirclement sealing. Embed the sealant strips into concrete grooves with depth not less than 1.5 times the strip diameter to prevent groundwater or rainwater from seeping into the pier through the joint. For concrete component surfaces, apply penetrating crystalline waterproof coatings with thickness not less than 1.5mm and penetration depth not less than 5mm to enhance the concrete's own impermeability.

4.3 Designing Reasonable Maintenance Space

Define maintenance space design standards: Establish differentiated space requirements for different components. For the interior of bridge box girders, the clear height between top and bottom slabs should be not less than 1.8m, and the clear width between webs not less than 1.2m. Set inspection holes every 30m, with protective railings around the holes. For pier maintenance, set up ring-shaped maintenance platforms around the piers, with platform width not less than 1.5m. Build the platforms with steel structure, bearing capacity not less than 2.5 kN/m². Install ladders between the platform and the ground, with safety cages on the outside of the ladders. For bearing maintenance, reserve inspection channels above the bearings, with channel width not less than 1m and protective railings on both sides. Also, set hoisting holes near the bearings to facilitate the operation of hoisting equipment during bearing replacement[9]. Optimize maintenance access and equipment interface design: Set longitudinal inspection walkways on both sides of the bridge, with walkway width not less than 1m, paved with anti-slip steel plates. Install 0.3m high separation barriers between the walkway and the deck to prevent vehicle intrusion. Reserve power and lighting interfaces near key components, with interface spacing not exceeding 50m, ensuring convenient connection for inspection equipment during maintenance. For long-span bridges, set inspection basket tracks under the main girders, arranged along the full length of the girder. The basket should have a load capacity not less than 2kN and be movable along the track, facilitating comprehensive inspection and maintenance of the girder bottom.

5.Conclusion

Through systematic analysis of municipal bridge design, this study clarifies that safety and durability are the core supports for a bridge's whole-life-cycle service. At the safety level, optimizing structural stress design can reduce structural damage risk through dynamic load simulation and redundancy design; improving protective facilities can build multi-level physical barriers to reduce accidental injuries; strengthening emergency evacuation design can enhance accident response efficiency. These three aspects synergize to form a safety assurance system. At the durability level, selecting optimal corrosion-resistant materials can reduce environmental erosion from the source; optimizing drainage and impermeability design can block water-induced damage paths; designing reasonable maintenance space provides convenience for later upkeep, collectively extending the bridge's service life. The research confirms that safety and durability design must be closely integrated with the bridge's usage environment and functional requirements. They are interconnected and inseparable; only through overall planning can bridge traffic safety, public interest, and urban transportation stability be effectively guaranteed.

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