

Research Progress of Fe-SMA in Seismic Resistance and Durability Enhancement of Bridge Structures

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Abstract. Iron-based shape memory alloys (Fe-SMA) have become a research hotspot in the field of bridge engineering due to their advantages such as shape memory effect, superelasticity and low cost. Due to the difficulty of traditional bridge materials in meeting both seismic resistance and durability requirements, this paper reviews the key performance of Fe-SMA application and the existing research gaps, providing a reference for future related research. This article mainly summarizes the seismic application forms of Fe-SMA in key parts of bridges and analyzes the seismic mechanism of this material regarding shape memory effect and superelasticity. Meanwhile, the research progress of Fe-SMA in enhancing the durability of bridge structures, such as fatigue resistance and corrosion resistance, was expounded. Previous studies have shown that Fe-SMA cannot only effectively enhance the seismic performance of bridges, but also has excellent fatigue resistance and corrosion resistance, which is expected to significantly extend the service life of bridges. There are still deficiencies in the research on Fe-SMA in enhancing the seismic resistance and durability of bridge structures. If it can be studied and improved in the future, it is expected to create tremendous value.

Keywords: Iron-based shape memory alloys (Fe-SMA); Shape memory effect; Bridge; Seismic resistance; Durability.

1. Introduction

As a core component of transportation infrastructure, the seismic performance and durability of Bridges are directly related to regional economic operation and public safety. In earthquake-prone areas, bridges are prone to beam displacement, bearing damage or even overall collapse due to seismic loads. Moreover, during long-term service, environmental corrosion and vehicle fatigue loads can lead to structural performance deterioration and shorten the service life. According to statistics, more than a thousand bridges are damaged by earthquakes worldwide each year, and about 30% of the existing bridges are facing the problem of insufficient service life[1]. Traditional seismic reinforcement and anti-corrosion measures have limitations such as high cost, frequent maintenance, and significant disturbance to the original structure. Therefore, it is necessary to explore new materials that possess both excellent seismic performance and durability to address this issue.

Fe-SMA, with its two core characteristics of shape memory effect and superelasticity, provides a new direction for the technological innovation of bridge engineering [1]. Fe-SMA has more advantages than other SMAs. Its production cost is much lower than that of other SMAs, and it has good seismic performance, unique fire resistance, high strength and excellent ductility[2-5]. Meanwhile, Fe-SMA can recover its original shape after being deformed under force by triggering temperature or stress. It can effectively dissipate seismic energy and reset structural deformation. Moreover, it has far superior corrosion resistance and fatigue life compared to traditional steel, which can reduce the need for later maintenance[3][6]. Therefore, evaluating the key performance of Fe-SMA application is of great value and practical significance for promoting the material to solve the core problems in the field of bridge engineering.

Existing research has extensively explored and studied the basic mechanical properties of Fe-SMA and has investigated its feasibility in enhancing local seismic performance and mitigating corrosion. This research centers on "Enhancing Seismic Resistance and Durability of Bridge Structures with Fe-SMA", aiming to systematically integrate the research achievements and technical bottlenecks in this field. Firstly, the basic characteristics of Fe-SMA and the core demands of seismic resistance and durability of bridges are expounded. Secondly, the application research of Fe-SMA in seismic-resistant components and durability improvement of bridges is classified and sorted out. Finally, the limitations of existing research in various aspects are evaluated, and the future research directions and application prospects are discussed.

2. Applications of Fe-SMA in Bridges

2.1. Basic Components of Bridges

The bridge deck section, which includes drainage and waterproofing systems and expansion joints, etc. It is typically made of asphalt concrete or cement concrete, which directly withstands the wear of wheels and protects the main beam from rain erosion. The load-bearing structure is the main load-bearing component of the superstructure of the bridge and comes in various forms, such as slab beams, arch rings, and slings. The piers and bridge columns are located in the middle of the bridge and bear the force from the bearings, such as the impact of wind or water flow. The bearing is an important load-transferring device, located at the top of the pier, which can transfer the loads from the superstructure to the substructure.

2.2. Application Methods of Iron-based Shape Memory Alloys in Bridge Reinforcement

2.2.1. Steel-concrete Composite Bridges

Poor construction methods can lead to nonlinear creep, excessive deflection and crack propagation[7]. Jakub Vůjtěch et al. studied a 15-meter-span bridge located in the center of Carlsbad. Due to design errors, the bridge had problems with cracks and deck deflection. For this, they designed a permanent reinforcement system using Fe-SMA bars: First, perforated rebar joints were installed on the lower surface of the bridge, and then 68 Fe-SMA rebars with a total length of 825 meters and threaded anchors were installed to the lower surface of the bridge through four holes on the rebar joints, with threaded connectors connecting the rebars. To apply prestress to the bridge for reinforcement, use resistance wires and heating ceramic pads of induction heaters heated to 300 °C for activation. The researchers also installed 17 half-bridge strain gauges on the lower surface of the bridge and had the bridge carry four 32-ton trucks before and after the reinforcement to test and record stress changes at different parts of the bridge. The test results showed that the average prestress loss of the bridge was 8.5%, much lower than the actual 20%, and the reinforcement system reduced the average mid-span deflection by 10 millimeters (9%). These data also validate the applicability of iron-based SMA in bridge reinforcement. Jakub Vůjtěch et al. also used a similar method to repair and reinforce a historic steel bridge (which has been in use for 113 years) in Petrov on the Desna River, Czech Republic [1]. This time they used iron-based shape memory alloy plates and selected one of the beams to reinforce the bottom flanges of the bridge beams. The Fe-SMA plates were installed from small temporary scaffolding erected under the bridge. First, the loose old screws of the lower flange of the crossbeam were hammered out, and the Fe-SMA plates, which were bolted at both ends between the two corners, were placed on the lower flange. Then comes the activation work, where the Fe-SMA plates are clamped between ceramic heating pads and wrapped in an insulating coating, and then heated to a maximum activation temperature of 260 °C for data detection, but since the number of ceramic heating pads available for activation is limited and half of the Fe-SMA plates are activated in each step, two activations are carried out. Experimental data indicated that the lower flange compressive stress was about -25 MPa after the first activation and about -8 MPa after the second activation, due to significant prestress loss during the secondary heating process. But it is undeniable that the effect of the reinforcement is obvious. Through Fe-SMA reinforcement, permanent compression of the

bottom flange of the crossbeam is achieved, and the static load on the structure is balanced. As mentioned above, the reinforcement method has significant advantages. First, the ceramic heating method is efficient, safe and suitable for field use. Second, the overall production cost of iron-based shape memory alloys is significantly lower than that of nickel-titanium shape memory alloys, and the material properties are similar to those of structural steel, so it is more suitable for civil engineering applications. More importantly, compared with traditional materials, Shape memory alloys generate recovery stress through the shape memory effect, do not require large tensioning equipment, and are less constrained by construction space.

2.2.2. Articulation Performance of Hollow Slab Bridges

Articulated joints provide crucial lateral connections within hollow slab (HCS) Bridges and facilitate load transfer between adjacent beams. However, articulated joints are prone to cracking, which is a common problem for HCS Bridges[8]. So Xinliang Sun et al. proposed laterally strengthening the hinge by using locally surface-mounted Fe-SMA rods. The experimental method involved preparing 13 panel beam hinge specimens and loading them under bending shear loads. The test series included two quantities of Fe-SMA rods (one and two), two activation lengths (100 mm and 200 mm), and three activation temperatures (unactivated, 200 °C and 400 °C). The study shows that this reinforcement technique can effectively enhance the lateral connection of adjacent HCS beams and the mechanical behavior of the hinge and also indicates that Fe-SMA can increase the load of the bridge and extend its service life[8].

2.2.3. Self-centering Techniques for Bridge Columns under Seismic Action

The repair techniques mentioned above are all applied to the superstructure of the bridge, that is, the bridge deck. Raza Saim and his team studied whether applying iron-based shape memory alloys to bridge columns could achieve the effect of self-centering after an earthquake, with residual drift being an important concept. It refers to the inevitable lateral or longitudinal displacement of bridge components, including bridge columns, during an earthquake, and the permanent displacement caused by the structural components not necessarily returning to their original positions after the earthquake movement. As a result, residual drift can seriously damage the functionality and service life of Bridges. Raza Saim et al. reduced the residual drift of bridge columns by combining Fe-SMA with traditional reinforcement materials to enhance the self-centering ability of bridge columns. In 2023, Raza Saim's team prepared four 1:4 scale models to simulate the bridge column, with variables including the number ratio of prestressed conventional bars and Fe-SMA bars, longitudinal bars, and initial prestress[9]. They first removed the concrete overlay of the original column by hammering and drilled holes at the bottom and top, and then installed the Fe-SMA bars longitudinally into the holes and grouted them. Then, Fe-SMA helical restraint bars were installed to prevent buckling and finally use an air torch to heat the Fe-SMA to 200 °C for activation to provide prestress and spray a layer of concrete cover on the surface. In 2024, they studied the seismic performance of Fe-SMA segment-based bridge columns and employed 3D printing technology[10]. This time they prepared two samples, each consisting of four cylindrical segments, and the construction method was similar to the previous experiment. In the first step, 3D printing was used to make the formwork shell and the segmented installation of the steel cage and the pipes for installing the Fe-SMA bars. In the second step, energy dissipation bars (ED steel) and Fe-SMA bars were installed and then stacked and connected, and finally grouting and assembled. The difference is that in this experiment they activated the Fe-SMA through resistance heating. The loading method for the two experiments was very similar. The built steel frame was connected to the hydraulic actuator located on the horizontal side and above, and then the test sample was placed in the middle of the frame for loading and several displacement sensors, including linear variable displacement sensors (LVDT), string potentiometers (SPOT), and laser sensors, were installed longitudinally and laterally for displacement detection. The hydraulic actuator above provided the gravitational axial load to simulate the static load of the superstructure on the bridge column, and the hydraulic actuator on the horizontal side provided the lateral load to represent the lateral displacement caused by the earthquake on the tip of the bridge column. Both experiments stopped loading when the drift rate reached 5%. The results of the experiments were as

expected. Both experiments demonstrated that the residual drift of the bridge columns with iron-based shape memory alloys was significantly reduced compared to those built with traditional reinforcing bars because Fe-SMA can provide self-centering and energy dissipation for the bridge columns. In the first experiment, when the target drift rate was 5%, the residual drift of the bridge column with Fe-SMA bars was 30%-60% less than that of the traditional bridge column, and when the ratio of the number of traditional bars to the number of Fe-SMA bars was 0.15, the energy dissipation and residual drift reached the best balance. The second experiment showed that the modified bridge column exhibited strong self-centering behavior, with an average residual drift of less than 1% at a drift rate of 3%. One was the reinforcement of existing bridge columns using Fe-SMA, and the other was the construction of prefabricated bridge columns using a combination of Fe-SMA material and 3D printing technology. Undeniably, Fe-SMA can play an important and effective role in both reinforcement and construction, thus, Prestressed Fe-SMA rods may serve as a promising alternative to traditional construction techniques.

3. Challenges and Technological Development

Research on the application of Fe-SMA in enhancing seismic resistance and durability of bridge structures still faces challenges. Traditional Fe-SMA has insufficient adaptability to extreme environments, making it difficult to cope with conditions such as seawater corrosion, storms, and high temperatures. There is a lack of targeted design for resisting extreme environments, which hinders the effective coordination to improve the overall durability of bridges. Currently, Fe-SMA does not possess active thermal response or water response capabilities and thus is unable to proactively protect bridge structures by altering its own performance when extreme conditions occur. The current research has rarely touched upon the long-term mechanical properties of Fe-SMA in extreme environments, and there is a lack of data to support the stability of its seismic reinforcement effect under the combined action of storm loads and seawater corrosion.

Future technological development can lead to the research and development of new environmentally responsive shape memory alloys, with a focus on the development of thermally responsive and water-responsive materials. These materials will automatically trigger shape recovery when the temperature reaches a specific threshold, counteracting the deformation of bridge structures, or form a protective layer on the surface when in contact with seawater, resisting corrosion.

4. Conclusion

Iron-based shape memory alloys are widely used in bridge reinforcement due to their shape memory effect. The high recovery prestress provided by iron-based shape memory alloys compared to traditional materials can be used to repair cracks in Bridges and enhance the strength of bridge bodies to achieve reinforcement and extend the service life of Bridges. Future research could focus on the reinforcement effect of iron-based shape memory alloys on Bridges under extreme conditions, as traditional building materials used to construct Bridges, such as concrete and wood, are often limited by extreme environments such as seawater corrosion, storms and high temperatures. There may be new types of heat-responsive and water-responsive shape memory alloys in the future to protect Bridges from the environment.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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