Effect of Shape Memory Alloy as Seismic Isolation Device in Bridge Construction

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Abstract— Shape Memory Alloys (SMAs), as the name suggests, are materials that, because of their special thermal mechanical properties, can "memorise" or recover its original shape when subjected to temperature or load. Super elasticity and the shape memory effect are two key characteristics that set SMAs apart from other types of materials. Researchers and engineers have worked very hard in recent years to create high-performance and resilient bridge systems. SMAs have consequently garnered a lot of interest in bridge engineering research. With a focus on bridge engineering, this study reviews in-depth the applications of SMAs in civil engineering that are currently in use, summarises research on various SMA-based bridge components, classifies the SMA characteristics that make them appropriate for the field of bridge engineering, and emphasises future development areas and opportunities.

Keywords: Shape Memory Alloy, Super Elasticity, Resilient Bridge System, SMA – Based Bridge

I. Introduction

To reduce the hazards of seismic damage to highway bridges, seismic isolation has been regarded as a dependable and cost-effective method. In order to protect a bridge structure from seismic damage, seismic isolation aims to change the bridge's natural period so that the dominating frequency of the earthquake ground acceleration can be safely avoided. Additionally, the energy dissipation mechanism and intrinsic dampening property prevent the bridge system from being overdisplaced. Experimental work, field data, and analytical research on the seismic response of isolated bridges during recent earthquakes have shown that isolation bearings can significantly enhance the seismic performance of bridges and, as a result, lower the cost of post-disaster repair and rehabilitation.

Laminated rubber bearings (LRB) and sliding bearings are the two major types of seismic isolation bearings that are available for this use. The sliding bearings have been used in both buildings and bridges and exhibit reasonably excellent performance under a variety of earthquake loadings. LRB is taken into consideration in this work. Laminated rubber bearings can support shear deformations and carry vertical loads in compression. The vertical rigidity of the bearing is increased by the rubber layers strengthened with steel shims, which decreases the freedom to bulge. As seismic isolation devices, laminated rubber bearings of three different types are frequently used: natural rubber bearing (NRB), lead rubber bearing, and (LRB). Since the mechanical behaviour of HDRB is greatly influenced by the magnitude, history, and rate of displacements experienced during earthquakes, it is difficult to describe it in terms of equivalent linear or bilinear models that do not capture the complex mechanical behaviour of HDRB under strong earthquake ground accelerations. Additionally, it was noted that very few studies, if any, took into account the nonlinear force-displacement relationship of the bridge pier, which takes severe earthquake ground accelerations into account. In this regard, additional studies are needed to determine whether utilising SMA-based isolation bearings (SRBs) in highway bridges subject to seismic loads is appropriate.

SMAs have polymorphism, like many other alloys, which means they can have many crystal structures and the same chemical makeup, as seen in Fig. 1. At higher temperatures and lower stress states, the austenite stronger structure (parental phase) remains stable. Martensite is more stable at lower temperatures and under high stress because its crystal structure contains less order.

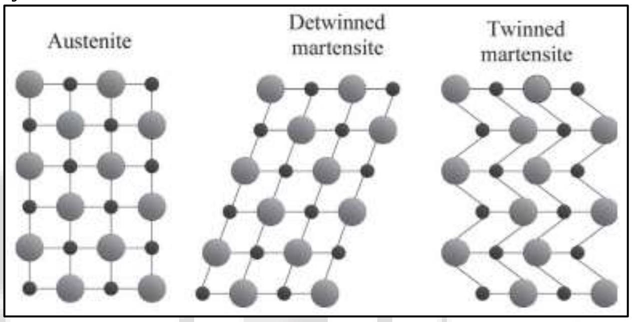

Fig. 1: Crystal orientations in different temperature states of SMAs.

The main objectives of this study are mentioned as follows:
A discussion of several types of SMAs' thermodynamic, physical, SME, and pseudo elastic (PE) behaviour as well as other features, as well as how effectively they work as vibration control mechanisms in civil engineering structures. Sorting and defining the most popular constitutive models for seismic and dynamic design given by SMAs.

II. Literature review

Shau Li et.al. (2019) analytically determines the effectiveness of a novel bridge system with superelastic SMA reinforced concrete pile. Exhibited that SMA RC piers & SMA restrainers effectively change the self-centring capacity and reduce seismic force damage due to SMAs lower stiffness. Revealed that Fe SMA had poor shape recovery limit and Fe-Mn-Al-Ni have super elasticity similar to conventional Ni-Ti SMA.

W S Tseng et.al. (2000) technical importance for the development of performance based seismic design & other methodologies for SMA RC bridge pier. Here, SMA was used as longitudinal reinforcement only at plastic hinge. Fe based SMA showed good workability, machinability, weldability & wide formation hysteresis compared to Ni-Ti SMAs.

Asoka Venkitaraman et.al. (2013) Described seismic vulnerability model of the bridge is developed through FEA under suitable modeling and analysisng

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conditions and found that retrofitting should be mainly focus on the region of expansion joint.

Rahman Bhuiyan et.al. (2013) studied that strength & distribution of bridge column in each deck segment between expansion joints are the primary factors which significantly affect the seismic response characteristic of bridge structure

Jaroni Mohd Janiet.al. (2011) Seismic performance analysis is conducted for a 3-span continuous highway bridge, which is subjected to moderate to strong earthquake ground acceleration in longitudinal direction and revealed that that seismic response of bridge are affected by different isolated bearings.

Wang et al. (2014) proposed a novel pseudoelastic SMA self-centring seismic base isolator in U-shaped dampers (SMA-UDs). They investigated two different designs, which incorporate the SMA-UDs into a conventional laminated rubber bearing with a lead core or with steel-UDs. Their findings have shown that the proposed base isolation system exhibits superior self-centering, adequate energy dissipation, stable and satisfactory flag-shaped hysteresis loops, a significant reduction in residual deformation under cyclic loading and ease of inspection and repair after a severe earthquake.

Dezfuli et al. (2012) The dynamic performance of a three-span continuous concrete-girder highway bridge structure was assessed under near- and far-fault motions, and another study provided a unique modelling approach of SMA wire based rubber bearings. According to the findings, SMA wires can effectively reduce shear strain demand in LRBs and limit deck movement by increasing the elastomeric isolator's effective stiffness. As a result, there may be a much lower chance of bearing failure and deck unseating. Furthermore, these cutting-edge bearings may significantly improve the seismic behaviour of bridges in terms of base shear due to the higher energy absorption capacities of SMA-LRBs.

Dezfuli and Alam (2013) The SMA wires were laid across the lead rubber bearing (LRB) in an asymmetrical double crossing configuration to create the innovative SMA-based LRB (Fig. 2). The suggested SMA-LRB demonstrated a much lower shear strain demand (up to 46% lower) and higher energy absorption when compared to conventional LRBs (up to 31 percent higher). Additionally, by reducing residual displacement by roughly 33 percent, the pseudoelastic influence of Fe-based SMA (above 13 percent strain) improves LRB re-centring performance. By enhancing its recentring characteristic, prestraining SMA wires, which is necessary in the procedure of putting wires on elastomeric vibration dampeners, may improve SMA-LRB performance. For instance, 3% pre-strained SMA wires could reduce SMA-LRB residual deformation by 19%.

III. Modelling

To characterize the incredibly complex behaviour of shape-memory materials, several researchers have so far concentrated on the martensitic phase change and proposed constitutive models. Either at the microscopic or macroscale, these models were made. Continuum mechanics establishes a correlation between deformation, strain, and stress at specific points using a minuscule amount of material. On the other hand, phenomenological models of the macroscopic level are aimed to describe the SMA reactions. Some of these models are built by fitting material characteristics to experimental data, while others are mainly based on thermodynamic concepts.

IV. Shape memory alloys seismic applications for civil engineering structures

SMAs have been used in many different applications in structures such as base isolation, bracing, cables and etc.

A. SMA – Based Vibration Control

In order to reduce the reactions and deformations of a structure subjected to high loading conditions, damping and re-centring properties of SMAs are used. We created SMA-based isolators for an uncoupled system that restricts the transfer of seismic input energy from the ground movement to the superstructure and is installed between a superstructure and substructure in a base isolation system. On the other hand, pseudoelastic SMAs can re-center the structure with less residual stress despite having a lower damping capacity.

B. Base Isolation Devices

Seismic isolation dampers' primary goal is to reduce the structure's exposure to induced seismic forces during an earthquake. The integrity of the structure is maintained as a result of the reduction in seismic excitation and structural deformations.

The superstructure, substructure, and isolator are the three main parts of constructions having SMA-based isolation devices. They are typically installed between the foundation and the first suspended level of buildings. Based on their exceptional qualities, including their strong damping capacity and re-centering capabilities, as described earlier, experimental tests have demonstrated that SMAs are practical and ideal choices for isolation devices. SMAs simply shine in these situations because of their inherent damping mechanism given by phase transformation, especially when an ideal isolator is anticipated to exhibit varied stiffness according to the base excitation.

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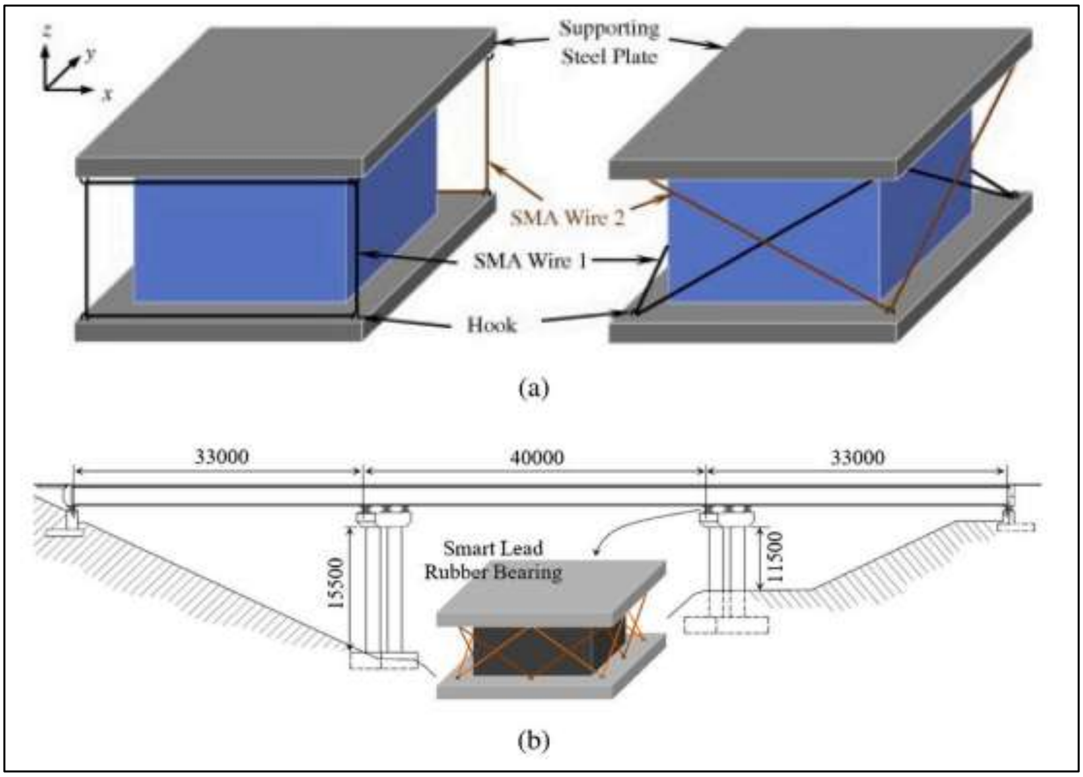

Fig. 2: SMA wire-based lead rubber bearing: (a) smart rubber bearing with straight and crossing SMA wires; (b) wire-based SMA-LRB isolator for a multi-span bridge (dimensions are in mm)

V. Summary of Practical Examples of SMA-Based Structural Vibration Control Devices

Because it is easier to implement than the shape memory effect (SME) characteristic, the pseudoelasticity trait provides the basis for the bulk of SMA applications in vibration control devices for civil engineering structures. As a result, the SME feature of SMAs as vibration control devices has a finite number of applications. As a result, the SME characteristic may be used more successfully as an actuator in various systems and equipment for controlling vibration.

The various uses of SMA-based structural control systems are enumerated by Alireza Tabrizikahou et al. in 2022. The application of SMAs in vibration control of civil engineering constructions is divided depending on type, device, and used mechanism in the table [7]. Additionally, each system is given five features in the final column, which are listed as following:

- Mechanism: based on shape-memory effect (A1); based on pseudoelasticity (A2)
- Cost: economical (B1); fair (B2); expensive (B3)
- Constructibility: easy (C1); moderate (C2); complicated (C3)
- Dissipation of energy: high (D1); moderate (D2); low
- (D3)
- Effectiveness: effective (E1); moderate (E2); limited (E3)

Based on the demonstrated SMA mechanism, the first set of features (A1 and A2) are assigned to each system (SME or PE). The system's manufacturing and implementation costs are determined by the second set of features (B1, B2, and B3), which include I the SMA material used (for example, the cost of Ni-Ti is significantly higher than Cu- and Fe-based SMAs); (ii) the amount of material required; and (iii) the cost of installation (for example, the installation of a base isolator on a historical building is significantly costlier than retrofitting a concrete beam).

A schematic classification of diverse applications according to the approach and system used is shown in Figure 3. Three types of SMA-based devices are distinguished: semi-active vibration control, active vibration control, and passive vibration control. Active vibration control is based on the shape memory effect, whereas passive vibration control is based on the pseudoelasticity of SMAs. Then, based on the readily available literature, the type of equipment and system is presented for each group.

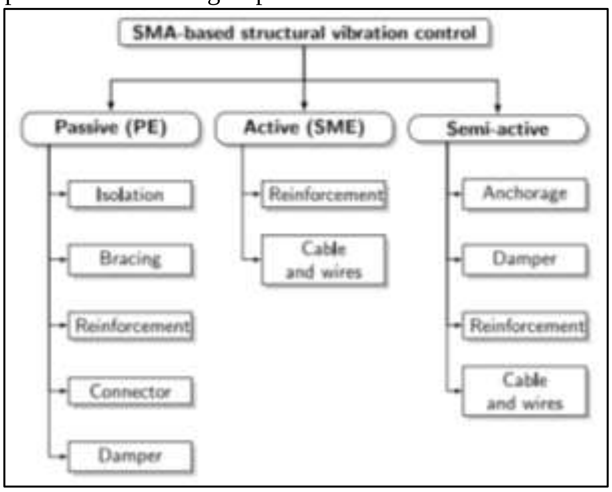

Fig. 3: Structural vibration control of SMA- based devices based on the used mechanism

VI. CONCLUSION

An up-to-date review of the usage of shape memory alloys in seismic response control systems was provided by this work. Numerous distinctive qualities of this innovative material provide new opportunities for the design and application of seismic devices for building and infrastructure systems. The numerical modelling and actual application of SMAs for vibration response control of civil engineering structures has advanced significantly. There are certain issues, though, that may be resolved. The results of this study and the current restrictions on the usage of SMAs in structural vibration control can generally be summarised as follows.:

- Due to the wide transition temperature range that some Fe-based SMAs (such Fe-Mn-Si-Cr) displayed, their practical applicability may be constrained. They are thermodynamically stable in civil engineering constructions at room temperature because they have a Ms close to 0 °C. For applications requiring constant stress or fluctuating temperatures, their propensity to generate fresh martensite (when cooled or loaded) poses a serious obstacle.
- Ni-Ti alloys have so far proven to have the most desirable characteristics for use in civil engineering, including high recentring ability, excellent fatigue resistance, high tensile strength, high recoverable elongation, and a number of other benefits. However, the extensive variety of structural applications are constrained by the high production costs and the precise manufacturing procedure. On the other hand, Fe-based SMAs have drawn a lot of attention since they behave very similarly to Ni-Ti but at a price that is significantly lower (8–12 times lower, hence the name low-cost SMAs).
- Despite significant advancements in numerical simulations of SMAs over the past few decades, the following problems may still be resolved: In order to accurately assess SMA-based vibration control devices, I many existing constitutive models on these devices are limited to a simple one-dimensional model; (ii) material constitutive models for SMAs with SE and SME properties should be more accurate with the capacity to estimate their exact reactions; and (iii) these constitutive models should be implemented into design and computational analysis software.

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