Shape Memory Alloys for Structural Engineering: An Editorial Overview of Research and Future Potentials

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Abstract

In the past few decades, the modern design philosophy of structural engineering has gradually shifted from preventing building collapse and loss of lives to high-performance objectives. However, traditional construction materials (e.g., concrete, wood, and steel) may not meet some of the high-performance structural design objectives under extreme disasters. The increasing demand for high-performance objectives has motivated the exploration of advanced structural materials. As a special type of advanced metallic material, shape memory alloys (SMAs) have been developed vigorously toward structural engineering in recent years. SMAs can withstand large strains and still recover the initial shape via heating (i.e., shape memory effect) or unloading (i.e., superelasticity). Both properties have different application prospects in the construction sector. This Special Issue has collected 30 high-quality research articles that can be categorized into three different groups: material and mechanical behavior of SMAs, shape memory effect of SMAs for prestressing and strengthening of structures, and SMA-based devices for energy dissipation and self-centering earthquake-resilient structures. Through systematic analysis of the existing research studies, this editorial summarizes the current state of knowledge and suggests future research directions and potentials for SMAs in construction.

Keywords: phase transformation; damping; seismic protection; energy dissipation; repair, prestress; state-of-the-art; research review.

1. Introduction

With the development of civil and structural engineering, the design philosophy of structures has been updated to a certain extent. Traditional construction materials may not meet high-performance

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structural design goals under extreme conditions. For example, modern concepts of seismic design allow structural engineers to design new buildings with the aim of predictable and ductile behavior in severe earthquakes to prevent collapse and safety, which relies on the "sacrificial" structural members that undergo considerable inelastic deformations at plastic hinge zones to provide energy dissipation. However, past earthquakes have shown that such concentrated inelastic deformation can result in residual/permanent drifts and are associated with damage that cannot be easily repaired. Consequently, these damaged structures must be demolished eventually, which leads to severe socio-economic losses due to reconstruction costs and disruption of building services. The current design concepts cannot meet the requirements of modern resilient and sustainable civil/structural engineering. Accordingly, the pursuit of high-performance structures has also greatly promoted the development of advanced materials.

As a special type of smart metal, shape memory alloys (SMAs) have developed vigorously in structural engineering in recent years. SMAs can withstand large strains and still recover the initial shape via heating or unloading. These features are attributed to the solid-to-solid transformation between two crystallographic phases, namely, austenite and martensite. Phase transformations can be thermally induced (known as shape memory effect) or mechanically induced (known as superelasticity), as shown in Fig. 1 (for the case of NiTi SMAs). Both properties are applied and used in structural engineering. For example, the shape memory effect of SMAs can be used to provide a prestress in the structural members and improve the service life of the structures. The superelasticity of SMAs is characterized by flag-shaped hysteretic loops, which represent appealing self-centering and energy dissipation capabilities in seismic protection and energy dissipation applications.

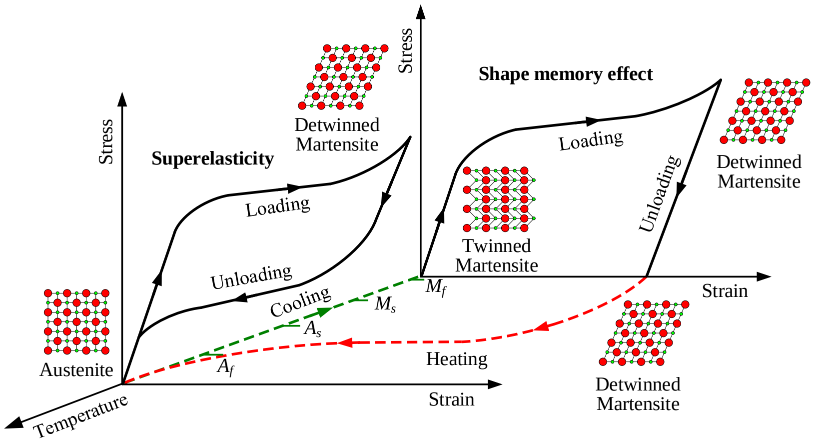

Fig. 1. A schematic view of the stress-strain responses of the shape memory and superelastic NiTi SMAs.

This Special Issue includes 30 high-quality articles that present the current state of the knowledge and the future research directions in the area of SMAs for structural engineering. A total number of 68 articles were initially submitted to the Special Issue. Each article has been peer-reviewed by international experts in the field. A total number of 30 articles were then selected for publication in this Special Issue. In summary, the articles can be categorized into three different groups. The first group focuses on the material and mechanical aspects of SMAs. From the material type point of view, this Special Issue provides the latest research results on NiTi-, Cu- and Fe-based SMAs in structural engineering. The second group discusses the shape memory effect of SMAs for prestressing, strengthening, and repair of structures. The third group aims to develop advanced energy dissipation devices, low-damage and self-centering earthquake-resilient structures.

A brief summary of the studies in each category is given herein and the areas that require more research in the future are highlighted.

2. Material and mechanical behavior of structural SMAs

2.1. Overview of the research

SMAs can show shape memory effect and superelasticity, which can be applied in civil engineering for prestressed strengthening and seismic shock absorption, respectively. From the material type point of view, the articles published in this Special Issue study the effect of manufacturing methods and post processes on the mechanical and thermomechanical behavior (such as superelasticity and shape memory effect) of NiTi- and Fe-based SMAs.

One of the novel methods for the fabrication of SMA parts is additive manufacturing [1], which can provide a single-step freeform manufacturing process that not only fabricates the complex geometries but also can be utilized to tailor the mechanical properties of the printed parts profoundly. In the selective laser melting (SLM) technique, the process parameters and scanning strategy show a remarkable effect on the microstructure, properties, and size accuracy of as-built parts. The NiTi tubes with three different thicknesses, which were fabricated using the SLM method, showed localized shear strains on the tube surface under pure torsional loading and exhibited a superelastic response with a stable transformation strain of 2.3% after 10 cycles [1]. Furthermore, the mechanical properties of hot-drawn NiTiNb SMA wires were investigated through monotonic tension, thermal excitation, and cyclic loading tests [2]. The mechanical properties of the hot-drawn SMA were then compared with those of the annealed ones. The results showed that under the monotonic loading, the yield and ultimate strength of the hot-drawn SMA are greater than the annealed one, and the maximum and residual recovery stress of the hot-drawn SMA increases. Moreover, the hot-drawn SMA has shown a better structural response in comparison with the annealed SMA in resisting the degradation of effective stress under an incremental cycle amplitude test.

Apart from the NiTi SMAs, recently Fe-based SMAs have received much consideration due to their relatively low-cost production (compared to NiTi), high shape memory effect, and prominent mechanical properties, which justifies their large-scale applications, particularly, in civil engineering. The study on the relationship between microstructure, shape memory behavior, and mechanical properties of a hot-rolled Fe-Mn-Si-Cr-Ni-Ti-C alloy showed that the hot-rolled alloy has a relatively good recovery behavior. The nano-sized Ti-C was already distributed in the as-rolled microstructure without aging heat treatment and facilitates the stress-induced γ to ε phase transformations [3].

The stress recovery behavior of the Fe-Mn-Si-Cr-Ni-VC shape memory alloy for prestressed strengthening was studied in [4]. The effects of different prestrain levels, activation temperatures, and initial preloads on the recovery stress were evaluated to propose an optimum activation strategy. According to the results, a prestrain level of 2% was found to be the optimum level when the activation temperature was below 200 °C. However, at higher activation temperatures, an increased prestrain resulted in an increase in the recovery stress. According to the fatigue test results, the recovery stress decreased by 12 – 15% after two million load cycles, regardless of the activation temperature.

The feasibility of using Fe-Mn-Al-Ni SMAs as prestressing elements in civil engineering was reported in [5]. Polycrystalline Fe-Mn-Al-Ni specimens were prestrained and subsequently heated up under constant strain in order to evaluate the prestressing potential of the material. Based on the results presented it can be concluded that the Fe-Mn-Al-Ni system is a promising alternative to conventional shape memory alloys used for prestressing applications eventually enabling novel and innovative applications in numerous civil engineering structures by utilizing the well-defined evolution of precipitates during activation.

2.2. Potential directions for future research

Controlling the manufacturing and post-processing parameters could improve the shape memory effect and superelasticity of SMAs for seismic shock absorption and active strengthening. On the other hand, despite the research done on SMAs in recent years, especially on Cu-based and Fe-based SMAs, there is still a lack of understanding related to the improvement of superelastic behavior [6] in these kinds of SMAs. Potential topics for future research related to SMA materials can be associated with their behavior in terms of creep and relaxation, corrosion (including galvanic and stress corrosion of prestressed members), hydrogen embrittlement, sustainable recyclability, fatigue, fracture, and finally additive manufacturing [7]. There is also a need for further development of low-price SMAs, such as Fe-SMAs, to provide cost-competitive solutions in the construction market.

3. SMAs for prestressed strengthening and repair

3.1. Overview of the research

The articles published in this Special Issue with regard to the strengthening and repair of existing structures can be divided into two categories: prestressed strengthening of reinforced concrete (RC) structures and prestressed strengthening of steel structures.

In the first category, SMAs are applied for the flexure strengthening [8] and shear strengthening [9] of RC beams; active confinement of RC cylinders [10] (solution could also apply to RC columns); strengthening of beam-column joints in RC frames [11]; combined flexure and shear strengthening of RC railway crossties [12]. The basic mechanism in the above studies is similar: applying SMAs to a stiff structure and generating prestress in the direction of concrete tensile stress or in the direction of concrete expansion, which can delay the cracking load in the concrete member. In the cases of flexure strengthening [8], shear strengthening [9], and active confinement of RC cylinders [10], the load carrying capacity and ductility are enhanced. In the cases of beam-column joints [11] in RC frames, the lateral load carrying capacity and energy dissipation are improved, however, ductility remains unchanged. The study of strengthening for railway crossties [12] suggests that the shear (diagonal) prestress can be effectively applied to the non-straight RC member, while the prestress loss is less than traditional prestressed steel bars.

The second category contains two studies aiming at the prestressed strengthening of steel structures against fatigue damage while maintaining the static load carrying capacity. Prestressed Fe-SMA strips have been used in [13] to improve the load capacity of a real 113 years-old steel bridge. The Fe-SMA strips were held by friction-based clamps that were bolted into the steel girder. The bottom flange of the steel girder underwent compression after strengthening, indicating an improvement in its fatigue problem, and at the same time, the static load capacity has been improved to meet the requirement for traffic load. Finally, the work [14] uses Fe-SMA strips for fatigue retrofitting of cracked steel bridge connections. The damaged double-angle connections were strengthened by prestressed Fe-SMA anchors, which resulted in a reduction in the negative bending moment in the connections and the maximum bending stress in the fillets of the connection angles.

3.2. Potential directions for future research

The articles published in this Special Issue demonstrate a great potential of prestressed SMAs for strengthening RC, steel, and glass [15] structures. It has been shown that the performances of RC beams in bending and shear, RC cylinders under compression, and RC beam-column connections have improved substantially after the prestressed SMA strengthening, while the fatigue resistance of steel beams under cyclic bending has been enhanced significantly. Despite the increasing number of laboratory studies focusing on prestressed SMA strengthening, there is still a need for large-scale applications of SMAs in construction (e.g., [13], [16], [17]). The existing techniques for SMA strengthening of structures mostly rely on mechanical anchoring systems, such as fraction-based and nail-based anchors. There is a need for more research on adhesively bonded SMA joints (e.g., [18, 19]), which offer a smooth gradual stress transfer and an enhanced structural integrity.

Potential future research directions related to SMA in construction can be on the development of simple constitutive models that could be utilized for numerical and analytical simulations of structural SMAs under sustained, monotonic and cyclic loading regimes. On the other hand, as SMAs are becoming a new class of structural materials, there is a need for a set of new design guidelines, recommendations, and standards that could be used by engineers for design purposes. Finally, given the importance of sustainable construction in the Net Zero 2050, the research shall be performed on the life-cycle analysis of SMA structural solutions, in which the recyclability of SMA material shall be taken into account.

4. SMA for low-damage and self-centering resilient structures

4.1. Overview of the research

The articles on the application of superelastic SMAs in mitigating damage in structures subjected to extreme loads like earthquakes can be grouped into three main categories: SMA-based connections, SMA dampers, and concrete SMA reinforcements. On the application of SMAs in developing new SMA-based connections, a study [20] proposed a new SMA-based connection for steel coupling beams to replace conventional RC coupling beams in earthquake-resistant structures. The new system utilizes superelastic NiTi bolts to connect the steel beams with shear walls. The study proved the efficacy of the new system in shifting the damage from the coupling beams to the non-expensive and easy-to-replace steel angles. Similarly, SMA bolts were studied in [21] as connecting elements in earthquake-resistant steel frames. The study proved the efficacy of the SMA bolts in developing partially self-centering systems that sustain limited post-earthquake inelastic deformations. A new SMA-based superelastic connecting device was presented and tested in [22]. The study demonstrated the efficacy of the proposed device in controlling damage when used in the connection region of steel frames. In addition, the anchorage systems for SMA cables were proposed in[23], which can successfully anchor SMA cables in seismic protection design. A study [24] investigated the fatigue characteristic of SMA strands. The superelastic and structural fatigue characteristics of SMA strands were evaluated under cyclic tensile loading at different strain amplitudes. The second group of studies published in the Special Issue focused on investigating the use of SMAs to enhance the self-centering capability. Two of the published works investigated the use of SMAs in developing friction dampers [25, 26]. Researchers in [25] studied the development of a hybrid damping system comprising self-centering SMA dampers and pall friction dampers. The study showed more effectiveness of the hybrid damper in enhancing energy dissipation and limiting residual displacements compared to using SMA or friction dampers individually. In an effort to further enhance the energy dissipation capability of SMA dampers, researchers in [26] studied experimentally and numerically the application of NiTi superelastic rods to connect friction wedges. The new hybrid damper showed a stable hysteretic response and a reliable self-centering performance. The application of SMA-based dampers in mitigating the seismic response of cable-stayed bridges was also studied in [27]. The proposed damper is in the form of a brace that can resist reversal loading with a buckling restraining mechanism. An innovative externally-hung rocking wall with SMA and disc spring devices to retrofit the existing buildings was proposed in[28]. The SMA devices were installed between the rocking wall and foundation to provide the self-centering capability for the structure. A novel SMA-magnetorheological hybrid bracing system was developed in[29], in which the energy dissipation capacity of the bracing system was increased significantly by activating the magnetorheological damper. Alternatively, the effectiveness of SMA-based isolation bearings for earthquake mitigation of bridges was also evaluated in[30, 31]. In addition, a modeling approach for an accurate representation of the strain amplitude effect was explored in[32]. Furthermore, the use of superlelastic Cu-Al-Mn SMA bar with a lumped mass was studied in [33] as a tuned mass damper (TMD) for structures prone to earthquakes. The study showed that the proposed TMD was able to reduce the structural peak acceleration by approximately 24%. Researchers in [34] studied the SMA-based TMDs and optimized them to control the seismic responses of the wind turbine towers. The Special Issue also presents studies that aimed at investigating the application of superelastic SMA bars as reinforcing bars in RC elements. A study [35] presented a numerical investigation to study the impact of replacing steel rebars at the plastic hinge region of RC shear walls with NiTi bars on strength reduction and overstrength design parameters. The application of SMA bars resulted in a reduced residual displacement and an acceptable seismic response as per FEMA's current design guidelines. A study on the cyclic response of mid-height RC shear walls with hybrid (SMA-steel) reinforcement was presented in [36]. The study showed that using relatively short SMA bars at the plastic hinge zone results in increasing the wall's ability to withstand high levels of drift without exhibiting significant residual displacement. The wall reinforced with the hybrid system showed a comparable lateral strength capacity to that of the steel-reinforced walls. A study [35] developed a precast column-to-foundation connection using ultra-high-performance concrete (UHPC) and NiTi SMA reinforcements. Low residual deformations were observed due to both the low damage in UHPC and the superelasticity of the NiTi SMA bars [37].

4.2. Potential directions for future research

The articles published in this Special Issue highlighted the great potential of SMAs in structural engineering applications. Whether used solely or in conjunction with other materials to develop new structural connections, dampers, or RC reinforcing elements, superelastic SMAs exhibit superiority in mitigating the deformation and damage in structural systems subjected to extreme loads. Despite the research done on SMAs in recent years, as a relatively new and emerging field, there is still significant room for critically needed knowledge for this field to mature further. For example, despite the importance of numerical and small-scale experimental investigations, there is a significant lack of knowledge related to the performance of SMAs in a full-scale realistic setup. Thus, there is a need for more large-scale experimental studies to validate and understand better the behavior of SMAs in full-scale structures. Furthermore, most of the research done on SMAs to date is focused on using NiTi alloys, which are considered cost-prohibitive for civil structural applications. More research efforts are needed in the manufacturing, testing, and modeling of large-scale SMA-based structural devices made of low-cost alloys such as Cu-based and Fe-based alloys.

Summary

Because of the inherent properties of shape memory effect and superelasticity, SMAs have become highly attractive to the community of structural engineering in recent years. The high-performance behavior observed in the SMA-based structural members/systems provides future potential in the area of structural engineering. The research topics in this Special Issue include three different groups: materials and mechanical behavior of SMAs, shape memory effect of SMAs for prestressing and strengthening structures, and SMA-based devices and self-centering earthquake-resilient structures. Although SMA research has made great progress in recent years, as a relatively new and emerging field, there is still significant room for critically needed knowledge for this field to mature further. Given the importance of sustainable construction for the Net Zero 2050, SMA-based structures and solutions may provide appealing strategies for life-cycle design. In addition to the currently widely studied NiTi SMAs, there is also a need for further development of Cu-based and Fe-based alloys, which can provide alternative cost-effective SMA-based solutions for structural engineering.

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