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Innovative use of a shape memory alloy ring spring system for self-centering connections

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ABSTRACT

This paper presents superelastic shape memory alloy (SMA) ring spring systems for seismic applications. The study commences with an experimental investigation looking into the mechanical performance of individual SMA ring springs under cyclic loading. The strength, self-centering ability, and energy dissipation capacity are shown to be dependent on the ring size as well as the treatment of the contacting taper face. Subsequently, a proof-of-concept beam-to-column self-centering connection is physically tested, shedding further light on the practical application of the ring spring systems for high-performance seismic resisting steel frames. The connection shows favorable cyclic behavior, with the majority of the deformation demand resisted by the SMA ring spring systems. The remaining structural components generally stay undamaged. Driven by the superelastic behavior of SMA, excellent self-centering ability with satisfactory energy dissipation is exhibited. A numerical investigation is then conducted to gain a further understanding of the load resistance mechanism of the proposed connection. The numerical model is validated against the experimental results with good agreement observed, enabling a further parametric study to be conducted taking a more in-depth look into the influence of ring precompression, taper face friction, ring size, and shear tab bolt preload on the overall performance of the connection. Based on the test and numerical data, some design comments are also made.

1. Introduction

Shape memory alloys (SMAs) are a unique class of metals capable of recovering large strains either by heating or unloading, depending on their thermal–mechanical state [1]. The material can have two prevailing phases, i.e. austenite phase at high temperature, and martensite phase at low temperature. The strain recovery property results from reversible martensitic phase transformations. When SMAs are deformed at a temperature above the austenite finish temperature A_f, the inelastic strain can be spontaneously recovered upon unloading, a phenomenon called superelastic effect (SE). On the other hand, when SMAs are deformed below A_f, the inelastic strain remains upon unloading but heating the material above A_f could promote strain recovery, where this phenomenon is known as shape memory effect (SME). Since the early development in the 1960s SMAs have been successfully applied in medical, aerospace, robotic, and automobile industries [2].

The potential of using SMAs, especially superelastic (SE) NiTi SMAs, for civil engineering applications was first recognized two decades ago by Chang and Araki [3]. The basic design intention was to utilize SE material to achieve a self-centering driving mechanism under seismic action, such that the post-earthquake residual deformation and the associated structural damage could be reduced. Another motivation for using SE SMAs was their energy dissipation ability attributing to reversible martensite interfacial motion, a damping mechanism which differs from dislocation based plasticity exhibited by other constructional metals such as steel. As a result of the these unique characteristics, flag-shape load-deformation responses are typically exhibited by SE SMA elements, and based on such behavior a variety of seismic resistant devices and members, including dampers [4–7], braces [8–9], beam-to-column connections [10–16], base isolators [17–18], and concrete members [19] were proposed. A series of experimental and numerical studies were carried out to assess their feasibility, and follow-up studies were conducted to evaluate the overall seismic performance of SMA-controlled structures [20–21].

From a practical implementation point of view, properly functioning SMA elements are the key to success for the development of SMA-based devices/members. The wire form of SMA, which is nowadays readily available in the market, is the most widely considered

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candidate due to its high material utilization efficiency and desirable deformation mode (i.e., uniaxial tension). The cyclic behavior of individual SMA wires under various loading rates and temperatures has been extensively studied and is well understood [22]. While the SMA wires generally show satisfactory mechanical properties, there are still practical issues related to their implementation. One problem is the difficulty of gripping (end fixing), especially for relatively large diameter wires, e.g., diameter larger than 1 mm. In addition, providing a sufficient level of load capacity means that a large number of wires need to be included in a device, which further complicates the arrangement of the wires and the gripping approach. It is also noted that the gripped part of the wire could be more prone to fracture due to local stress concentration. To address these issues, bundled SMA wires have been proposed that show promise in achieving comparable performance to that of individual SMA wires [23]. Alternatively, SMA bolts/tendons could be used to offer large load resistance, but it was found that their threaded parts are very susceptible to fracture [11,24–26]. While this failure mode could be mitigated by increasing the local cross-section area of the threaded part, this is realized at the cost of considerable material wastage during the machining process. Other element types such as SMA helical springs [27] and Belleville washers [28,29] have also been investigated, however their load resistance may not be large enough for civil engineering applications because the material within these elements is not fully mobilized when loaded. Use of SMA plate in beam-to-column connections has also been considered by researchers [30].

It can be seen from the above discussion that SMA elements selected for civil engineering applications should preferably exhibit the following properties: (1) high material utilization efficiency (i.e., economical), (2) low risk of damage, and (3) ease of installation. To cater to these requirements, an innovative type of SMA element, namely, an SMA ring spring is proposed and examined in this paper. The study starts with an experimental investigation looking into the mechanical performance of individual ring springs under cyclic loading, where the strength, stiffness, self-centering ability, and energy dissipation capacity are studied in detail. Subsequently, a proof-of-concept beam-to-column self-centering connection equipped with the SMA ring spring system is physically tested, and numerical investigations are then conducted, leading to preliminary design comments made for such connections.

2. Basic characteristics of SMA ring springs

The basic load resistance mechanism of a SMA ring spring lies in the development of hoop stress when subjected to external loading. As illustrated in Fig. 1, a typical SMA ring spring system consists of a series of superelastic SMA outer rings and high-strength steel (HSS) inner rings stacked in alternation with mating taper faces. When the system is compressed, the SMA outer rings expand due to the wedging action, and concurrently the HSS inner rings are squeezed but stay elastic. As a result, a high level of resisting load is provided by the vertical component of the contact force over the taper faces between the outer and inner rings. Upon load removal, the superelastic effect promotes self-contraction of the SMA outer rings, and hence the deformation of the entire system can be recovered. When the system is under cyclic load, energy can be dissipated via inherent damping of the SMA material. The friction effect may further promote energy dissipation, depending on the treatment of the taper faces. While the deformation capacity of the system can be readily adjusted by changing the number or geometric configuration of the rings, normally a limited number of rings are required due to the high deformability of the SMA. This enables a compact design of SMA-based devices and members. Furthermore, unlike SMA wires or bars which may experience fracture under excessive deformations, the SMA ring spring system is ‘locked’ when the gaps between the inner rings are fully consumed, a mechanism which effectively prevents damage to the SMA outer rings.

For each individual SMA outer ring, the controlling geometric dimensions include the external diameter (D_e), height (H), ring thickness (T), and taper angle (α), as illustrated in Fig. 1. A preliminary numerical study conducted by the authors confirmed that when the geometric dimensions are appropriately designed, the SMA outer springs can have a well mobilized hoop stress distribution over the ring cross-section, which reveals an effective utilization of the material [31]. The key factors that influence the behavior of the SMA ring spring systems were revealed, and appropriate geometric configurations of the rings were recommended. It was concluded that a taper angle (α) of 21.8° could ensure a desirable hoop stress distribution. As an important continuation of the previous numerical study [31], the current study focuses on physical verification of the ring spring system as well as experimental evaluation of its practical application. The experimental program consists of two test phases: (i) Phase-I test, where the cyclic performance of individual SMA ring springs is investigated; and, (ii) Phase-II test, where a proof-of-concept self-centering beam-to-column connection incorporating the SMA ring spring systems is designed and tested.

3. Phase-I test: individual SMA ring springs

3.1. Test specimens

The aim of this test phase was to understand the basic hysteretic properties of individual SMA ring springs. The main testing parameters included ring thickness, taper face friction, and loading protocol. A consistent taper angle (α) of 21.8°, as recommended by the previous numerical study [31], was adopted for all the test specimens. The height (H) of each specimen was 10 mm, and two ring thicknesses (T) of 3 mm and 5 mm were considered, leading to external diameters (D_e) of 40 mm and 44 mm, respectively. The inner cylinders, which have the same function as that of the aforementioned inner rings, are constructed from 38CrMoAl alloy and designed to match the taper angle of the SMA outer ring. Two contacting conditions, greased and non-greased, were employed over the taper face between the outer ring and the inner cylinders. A deformation capacity of 5 mm was designed for each SMA outer ring, and once the upper and lower inner cylinders contacted each other, no further room for deformation was available. By limiting this maximum compression, the peak hoop strain is kept within 7%. In order to assess the hysteretic repeatability of the specimens under various loading conditions, two loading protocols were considered, namely, constant amplitude and incremental amplitudes. For the former case, the specimens were subjected to 30 loading cycles with a constant amplitude of 5 mm; for the latter case, the specimens were loaded with incremental deformations from 1 mm to 4 mm with an 1 mm interval (two cycles per amplitude), and finally by 20 cycles with an amplitude of 5 mm. It should be noted that high-cycle structural fatigue performance of the SMA rings was not studied in this experimental program, and in addition, the possible temperature excursion effect was not measured.

The SMA outer rings are made of commercial Ti-50.8at.%Ni (i.e. 50.8% atomic percentage of nickel with the balance contributed by titanium) SMA material. The alloy was processed by hot rolling at temperatures between 800 and 900 °C, and was forged and straightened to a final diameter of 45 or 50 mm. The large-diameter bars were first machined into a number of 10 mm-thick stub tubes, and each segment was then machined into the desired outer ring shape. The outer rings were then heat treated at 400 °C for 30 min and finally water quenched. According to the information provided by the material supplier, the nominal austenite finish temperature (A_f) is around 10 °C. For comparison purposes, two additional aluminum outer rings were also produced and tested. The aluminum ring tests were conducted to highlight the unique superelastic property of SMA, and to clearly show how this effect changes the load-deformation characteristics of the ring spring systems. The aluminum outer rings were subjected to 5 loading cycles with a constant amplitude of 5 mm. All the SMA and aluminum