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A study of hybrid self-centring connections equipped with shape memory alloy washers and bolts

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A B S T R A C T

This paper presents an innovative type of hybrid self-centring extended end-plate connections incorporating high strength bolts and two basic SMA elements, namely, SMA Belleville washers and SMA bolts. The fundamental mechanical characteristics of the individual SMA elements were first understood via cyclic tests, and subsequently a comprehensive test programme on of four proof-of-concept connections with varying bolt dimensions and washer arrangements was conducted. The connection specimens exhibited flag-shape hysteretic responses with good self-centring ability and cyclic loading repeatability. Satisfactory ductility accompanied by moderate energy dissipation capacity was also shown, and it was found that the SMA washers contributed evidently to the strength, stiffness, and energy dissipation of the connections. A numerical investigation was subsequently performed to enable a more in-depth understanding of the connection behaviour, and it was further shown that increasing the preload levels of either the SMA washers or the SMA bolts could effectively increase the connection stiffness. A design model was finally proposed which enables an idealised bi-linear description of the moment-rotation responses of the hybrid self-centring connections. The design stiffness and strength obtained from the proposed models were found to agree reasonably well with the test results and numerical predictions.

1. Introduction

Steel moment resisting frames (MRFs) are a prevailing class of lateral load resisting systems for multi-storey and high-rise building structures. They are often deemed to have satisfactory seismic performance under strong earthquakes, provided that large inelastic deformations with sufficient ductility intentionally occur in specific members such as steel beams [1]. However, the 1994 Northridge and 1995 Kobe earthquakes exposed deficiencies of conventional beam-to-column connections which experienced extensive weld fracture. After these major events, the ductility performance of such connections has been carefully re-visited, and extensive follow-up investigations have been conducted, leading to improved connection design. These post-Northridge prequalified connections, either fully-restrained or partially-restrained, are expected to ensure life safety for the occupants by providing large inelastic rotations while maintaining their strength without significant degradation.

However, the plastic deformations induced at or near these connections are not easily recoverable, and thus permanent residual drifts could remain at the end of seismic excitations. A study conducted by McCormick et al. [2] found it impractical to repair damaged structures when the residual drift is greater than 0.5%. Even if the structures are repairable, decision makers can be faced with a dilemma of whether or not to repair them as the cost of the repair work can be prohibitively high. Moreover, the prolonged suspension of building functions hinders the community to rebound effectively from infrastructure disruption and business downtime. Some critical facilities, such as hospitals, government headquarters, and military facilities, cannot afford even a short occupancy suspension due to their unique purposes of service. Furthermore, multiple earthquakes, e.g., main-shock and aftershock sequences, could result in accumulation of permanent residual deformation [3]. Therefore, earthquake resilient structures which exhibit low levels of residual drifts nowadays become one of the hottest subjects among the community of seismic engineers and researchers. To this end, a novel category of seismic-resisting structures, namely, self-centring structures, has been proposed [4], and among the various available solutions, endowing the beam-to-column connections with self-centring abilities has attracted great attention.

The concept of self-centring connections was first realised by the application of post-tensioned steel tendons, anchored at the external or

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other selected columns parallel to the steel beams [5,6]. The self-centring driving force is provided by the connection gap opening that induces elastic elongation of the steel tendons/cables. Meanwhile, the commercial availability of superelastic shape memory alloys (SMAs) motivated researchers to develop alternative solutions for self-centring connections. The 'superelastic effect', which is triggered when the SMA is deformed in the austenitic form, allows the stress-induced deformation (up to 10% strain) to be recovered spontaneously upon unloading, and due to reversible microstructural interfacial motion, hysteresis loops are developed when SMA is under cyclic load [7]. The SMA solution may have the benefits of easy installation, compact size, no extra compression to steel beams, and good corrosion resistance. Some preliminary studies suggested that compared with conventional MRFs, an appropriate arrangement of SMA connections could lead to significantly reduced residual inter-storey drifts and concurrently well controlled peak deformation [1,8].

As for detailing, Ma et al. [9] proposed a prototype connection type which is modified from conventional extended end-plate connections, where the high-strength bolts were all replaced by SMA bolts. This idea was then verified through an experimental study [10], where good self-centring ability with moderate energy dissipation was shown. However, the shear resistance of these connections was solely provided by the friction between the end-plate and column face, a mechanism which is unreliable under large shear forces [11]. Penar [12] and Speicher et al. [13] performed a series of proof-of-concept tests on shear tab steel connections with external SMA bolts. Satisfactory hysteretic behaviour with improved shear resistance was seen, but the issues of installation complexity and floor-slab interference were not adequately considered in the study. In addition, the torque applied to the shear tab bolts induced friction which had detrimental influence on the self-centring performance. Some researchers attempted to add low yield strength steel angles to increase the energy dissipation of SMA-based connections [14–16], and the test results showed that this had to be realised at the cost of increased residual deformation. Other proof-of-concept SMA connections including innovative SMA components (e.g. SMA ring springs) are also under investigation [17–20].

In this paper, a new type of self-centring connection, namely, hybrid self-centring connections with high strength bolts, SMA Belleville washers and SMA bolts (abbreviated as SMA-WB connections), is proposed. The development of this connection type is inspired by the aforementioned SMA-based extended end-plate connections, but is modified to enable a more appropriate load resisting mechanism. In the following discussions, the key properties of the two SMA elements used for the connection, i.e., SMA Belleville washers and SMA bolts, are introduced first. After understanding their basic mechanical characteristics, proof-of-concept SMA-WB connections are physically tested, which is followed by a detailed numerical investigation. Design comments on such connections are finally made, and analytical models are also developed to facilitate practical design.

2. Basic characteristics of key SMA elements

2.1. Concise principle of SMA-WB connections

As schematically illustrated in Fig. 1(a), the proposed SMA-WB connections typically include a series of external SMA bolts and sets of SMA Belleville washers for the internal bolt row. The external SMA bolts are mainly used to provide moment resistance as well as self-centring driving force. Standard high strength (HS) bolts, which are used in conjunction with the SMA Belleville washer sets, are employed for the internal bolt row. The shear resistance of the connection is mainly provided by the HS bolts, and in addition, aided by the friction between the end-plate and the column face. The SMA Belleville washers are used to offer a certain level of rotational flexibility for the HS bolts and concurrently to promote self-centring and energy dissipation. With this arrangement, the deformation of the internal bolt row during loading is mainly provided by the SMA Belleville washers and, hence, minimises any permanent deformation that may occur in the HS bolts. The proposed SMA-WB connections can also have minimal spatial interference with the adjacent structural members such as the minor axis beam-to-column connections. Moreover, the installation procedure is similar to that used in conventional end-plate connections.

2.2. SMA Belleville washers

Belleville washers, also known as disc springs and sometimes simplified as washers, are traditional mechanical components that can be used with different stack patterns to provide different combinations of load resistance and deformability. As shown in Fig. 1(a), the governing geometric parameters for a Belleville washer include the external diameter (D_e), internal diameter (D_i), height (H), thickness (T), as well as cone angle (θ). A group of Belleville washers can be stacked in series or in parallel, where the former combination leads to increased deformability but unchanged resistance, whereas the latter one results in increased load resistance but unchanged deformability. The annular conical shape of Belleville washers enables relatively stable and concentric force transmissions with small installation space required.

By endowing Belleville washers with superelastic properties, much larger recoverable deformations accompanied by hysteretic damping could be promoted, and, as a result, the application can be further broadened. In fact, the idea of SMA Belleville washers (hereafter simplified as SMA washers) had been implemented by researchers since the 1990s, where the main focus at that time was given to their applications in the field of electrical engineering [21]. The thermo-mechanical producing process for SMA washers was discussed by Maletta et al. [22]. A more relevant study carried out by Speicher et al. [23] showed that the damping performance of SMA washers could be unsatisfactory due to an inappropriate design of the cone angle. By conducting a series of numerical investigations, some recommendations on the key geometric parameters have been proposed [24], based on which a representative SMA washer, with the dimension marked in Fig. 1(a), was designed for the current study. The superelastic SMA washers were directly ordered from the supplier SAES Smart Materials (www.memry.com). Per information from the supplier, the composition of the washers was 55.87% nickel by weight with the remaining contributed by titanium. Each washer had a maximum deformation capacity (H_0) of approximately 2.7 mm. The typical cyclic test result at room temperature (23 °C) is given in Fig. 1(b), showing satisfactory self-centring ability, repeatability, and energy dissipation capacities. Details of the test arrangement for the individual washers can be found elsewhere [24]. A consistent geometrical configuration was considered for all the SMA washers used in the current test programme.

2.3. SMA bolts

A uniaxial bar is one of the most widely considered forms of SMA products due to its high material utilisation efficiency. Through extensive investigations since the 1990s, the cyclic performance of individual SMA bars is nowadays well understood. For structural engineering applications, SMA raw bars are often machined into the bolt form. In this study, two nominal bolt shank diameters, namely, D_1 = 8 mm and D_1 = 12 mm, were considered. For the 8 mm diameter bolts, the total bolt length (L) is 240 mm or 290 mm; and for the 12 mm diameter ones, a consistent L of 290 mm is employed. Details of the bolt geometric configuration are given in Fig. 1(a) and Table 1. The SMA bolts were machined from commercial superelastic raw bars, which were purchased from the same material supplier (i.e., SAES Smart Materials) with the same composition as that of the SMA washers. Material coupon tests were conducted on typical 8 mm-diameter SMA bolts, and the hysteretic stress-strain response at room temperature is given in Fig. 1(b). The material test stopped due to the limitation of the capacity of the tensile machine.