Cyclic behaviour of an innovative extended end-plate connection with shape memory alloys

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ABSTRACT

Shape memory alloys (SMAs), with superelastic and shape memory effects, have attracted research interests in civil engineering in recent decades. Many research endeavours have been made to investigate the feasibility of SMAs applications in column-to-beam connections, aiming to minimise or even eliminate permanent post-earthquake deformations in main structural members. In this paper, an innovative extended end-plate (EEP) connection incorporating SMA bolts, high strength (HS) bolts and SMA Belleville washers is introduced which has been numerically investigated by the co-authors previously. This paper presents experimental data for the first time to prove the feasibility of the connection. One full-scale test is conducted under cyclic loading. Besides, the hysteretic performance including ductility, strength, self-centring performance, and energy dissipation is studied. The test results show that the innovative connection possesses excellent deformation capacity, self-centring ability, with moderate energy dissipation ability under seismic loading. More experimental and numerical works are currently in progress in order to further understand the structural performance of this type of hybrid connection.
1. INTRODUCTION

Shape memory alloys (SMAs) as a member of smart material family possess two unique properties, i.e. superelasticity effect (SE) and shape memory effects (SME), which enable their extensive applications in various fields, such as aerospace, automotive, robotics, and biomedical domains (Mohd et al. 2014). The realisation of these material properties mainly relies on the phase transformation between martensite and austenite. If the material deforms under the finish temperature of austenite ($A_f$), it can completely return to the original shapes by heating to above $A_f$, which is known as SME. If the material deforms at above $A_f$, the deformation can be spontaneously restored after unloading. Besides, the movement of the martensitic interface in inelastic deformations can dissipate energy, which is known as SE (Song et al. 2006; Tyber et al. 2007; Jani et al. 2014; Kim and Miyazaki 2015). It has been found that SMAs could withstand large repeatable and recoverable deformations (up to 8%-10% in strain for SMA bar), meanwhile possessing high damping, durability and fatigue resistance (Song et al. 2006; Fang et al. 2016). These properties enable SMAs to perform well under extreme, repeated even diverse loading conditions (e.g. earthquake) and hence has attracted increasing research interests in recent decades in civil engineering application, especially in the seismic engineering field (Mohd et al. 2014).

The commonly used design concepts for seismic-resistant connections, e.g. ‘strong-connection-weak-beam’, mainly focus on ensuring the plastic hinge occur in beam section nearby the connection area under earthquakes, aiming to prevent instantaneous collapse of structures and to ensure the safety of human lives by allowing the damage in main structural members during earthquake (Ghobarah et al. 1990; Tsai et al. 1995; Sumner and Murray 2002; Sawaguchi et al. 2016). However, the post-earthquake repair work of the resulted permanent deformations in structures are both costly and difficult (Fang et al. 2014). With an in-depth knowledge and understanding of the aforementioned properties of SMAs, many research endeavours have been made to investigate the feasibility of SMAs applications in self-centring column-to-beam connections to accommodate the deformation within the connections, thus allowing the adjacent members to behave elastically during a major earthquake (Mohd et al. 2014).

Ocel et al. (2004) firstly introduced martensitic SMA bars into column-to-beam connections, in which two SMA tendons were located outside of the beam flanges to connect the column flange and transferred the main moment. The connection showed satisfactory ductility with stable energy dissipation under cyclic loading up to 4% drift, and nearly 74% of the beam tip displacement could be recovered by heating. DesRoches et al. (2010) numerically investigated and compared the cyclic behaviour of two beam–column connections equipped with austenitic and martensitic SMA bars, respectively. It was found that the former novel connection exhibited lower maximum deformation while the later one showed less residual deformations in structure. Similar results were also found by Ellingwood et al. (2010). Moreover, Hu (2008) proposed that
SMA-based connections could be introduced to connect normal steel members since the SMAs could offer self-centring force for the connection and the normal steel members could provide stable energy dissipation. The feasibility of this concept was validated by a study of a CFT (concrete-filled tube) column-to-steel beam connection equipped with SMA and steel bars, and it was observed that the connection exhibited excellent re-centring ability and good energy dissipation performance under seismic loading (Hu et al. 2011; Hu and Hwang 2013). Subsequently, steel angles were introduced to combine with SMA bolts to develop a clip-angle connection between CFT columns and steel beams, and similar results were also characterised (Hu et al. 2013). Recently, Wang et al. (2015) applied this design concept in an I-beam-to-CHS column connection and suggested that the composite connection also showed a perfect re-centring capability with a moderate level of energy dissipation under cyclic loading.

Ma et al. (2007) firstly proposed a self-centring extended end-plate (EEP) connection via replacing the traditional high strength (HS) steel bolts by SMA bolts. The SMA bolts would provide the connection moment capacity and a re-centring capability upon unloading. Because of the SE behaviour of the SMA bars, the connection is also able to dissipate the moderate amount of energy during cyclic loading. This concept was strongly supported by both numerical and experimental studies conducted by Ma et al. (2008), Yam et al. (2015) and Fang et al. (2014). However, it should be noted that in this type of connection the direct shear from the beam member is designed to be transferred to the supporting column through the friction between the end-plate and the column flange since it has been found that SMA bars generally showed poor mechanical performance under direct shear (Fang et al. 2015). In order to enhance the shear capacity of the connection, Fang et al. (2015) proposed an improved connection, namely an HS-SMA hybrid connection. The basic concept is that the SMA Belleville washers with good re-centring capacity and a certain amount of energy dissipation ability are employed to equip the HS steel bolts in order to provide sufficient space for the deformation of the connection, and hence to protect the HS bolt from plastic deformation under cyclic loading. Therefore, the HS steel bolts can be left to resist the direct shear force and the SMA bolts are used to provide the connection moment capacity with the self-centring ability and moderate energy dissipation capability. The feasibility of this innovative connection has been numerically studied by the co-authors (Fang et al. 2015; Yam et al. 2015), however, experimental evidence is not available.

This paper presents the test results of an HS-SMA hybrid connection subject to cyclic loading in order to prove the feasibility of this type of connection. The main structural behaviour including strength, rigidity, ductility, self-centring ability and energy dissipation capacity are discussed in detail.

2. EXPERIMENT PROGRAMME
2.1 Test specimens and test set-up

The specimen considered in this paper is a three-row bolted EEP connection. Two SMA bolts are located at the top and bottom row with thick steel washers in order to provide sufficient length of the SMA bolts for improving the ductility of the connection (Fang et al. 2014). Two HS steel bolts are placed in the middle row as shown in Fig. 1(a). Each HS bolt is equipped with two groups of SMA Belleville washers, one group located in the inner side of column flange, the other on the end-plate side. Each group contains two pieces of SMA Belleville washers arranged in series. The detailed dimensions are shown in Fig.1(a). Structural members of the sub-frame in this paper including a beam and a column are purposely over-designed to make them respond in the elastic range during the entire test, and thus the deformation of the structure is mainly provided by the connection rotation. The end-plate of the beam as well as the column flange are designed as 'thick plate' to avoid the prying action on the bolts. Two continuous plates are introduced to enhance the strength of the panel zone to ensure the occurrence of the connection deformation in the bolt group. Extended stiffener plates are welded between the end plate and beam flanges to strengthen the moment-rotation capacity of the connection. A typical set-up of the test is illustrated in Fig. 2. The top and bottom end plates of the column are fixed on the loading frame by the bolted connections. A double acting cylinder (with a pushing/pulling capacity of 30/15 tonnes and a stroke capacity of 406 mm) for applying cyclic loads to the specimen, is pin-connected to the beam tip with 1025 mm distance from the column flange.

2.2 Instrumentations

Displacements and deformations of the specimens are monitored by a series of linear variable differential transformers (LVDTs) and strain gauges. The detailed arrangements are illustrated in Fig.1 (b). LVDT 1 and 2 are installed on the thread head of the SMA bolts located on the top and bottom row to measure the elongation of the SMA bolts; LVDT 3 and 4 located at 250 mm apart are employed to measure the deformation of the end plate; LVDT 5 and 6 are mounted on the HS bolt heads to measure the deformation of the SMA washers; LVDT 7 is located directly below the end plate to monitor the slip between the end plate and the column flange, and LVDT 8 is placed right under the loading point to measure the beam tip displacement.

Two strain gauges are installed along the shank on the opposite sides for each SMA bolt to measure the pre-stress value of the SMA bolts. The end plate, the extended stiffeners and the beam flanges are also equipped with strain gauges to ensure the loading is applied properly and to monitor the strain development on these main members.
2.3 Test procedure

Prior to the formal test, each SMA bolt and washer are pre-stressed to around 230 MPa to ensure that the connection is with a certain level of initial rigidity and reliable self-centring performance. The pre-stressing force in SMA bolts is loaded by strain control, which could be measured by the strain gauges (1-8) (Fang et al. 2014). On the other hand, the pre-stressing on the SMA washers is loaded by stroke control, which is measured by the LVDT 5 and 6. Subsequently, the cyclic loading is applied at the beam tip by the double acting cylinder with stroke control. The whole test is conducted according to the SAC Specification (AISC/AISC 2016), taking the ‘drift’ as the control parameter, which is calculated by beam tip displacement dividing the arm length (1025 mm) in this paper. Detailed drift levels include 0.375% (3 cycles), 0.50% (3 cycles), 0.75% (3 cycles), 1% (4 cycles), 1.5% (2 cycles), 2% (2 cycles), 3% (2 cycles), and 4% (2 cycles).

3. TEST RESULTS AND DISCUSSION

The description of the test results is followed by the discussion on the cyclic performance of the novel connection, including strength, rigidity, ductility, self-centring behaviour and energy dissipation ability. At the beginning, a brief introduction of various concepts of rotations is made, namely total rotation, plastic connection rotation ($\theta_p$) and concentrated connection rotation ($\theta_c$).

Total rotation of the system determines the rotation capacity of the whole structure. In this study, it can be considered as the ‘drift’, which contains $\theta_p$ and the elastic rotation induced by the elastic deformation of the main structural members (i.e. beam, column, endplate) (Fang et al. 2014). $\theta_p$ is one of the most important indexes for quantifying the ductility of connection. It was found that the ductility determined the inelastic deformation capacity of structure (Roeder 2002). For the typical cantilever beam test system in this paper, $\theta_p$ can be obtained by subtracting the elastic rotation from the total rotation based on the following formula (Venture 1997; Stojadinović et al. 2000):

$$\theta_p = \frac{\Delta - P/K_e}{L}$$

where $\Delta$ is the beam tip displacement; $P$ is the applied load; $K_e$ is the elastic stiffness, which can be predicted by the finite element (FE) model or theoretical calculation, and $L$ is the arm length. Besides, $\theta_p$ can be divided into $\theta_c$ and the plastic rotations induced by the plastic deformation of the main structural members ($\theta_{p,m}$) (Fang et al. 2014). The $\theta_c$ can be determined by the readings of LVDT 3 and 4, which is usually employed to calculate the initial stiffness of the connection (Penar 2005).
Fig. 1  Test arrangements: (a) geometric configurations of specimens, (b) instrumentations
Fig. 2 Typical set-up of the cyclic test

Fig. 3 Moment-plastic rotation curve
3.1 Moment-rotation response

The specimen exhibits stable structural performance under cyclic loading. With the increase of the load, a significant angle is developed between the end plate and the column flange. The angle opened in clockwise (+) and counterclockwise (-) directions when the beam is subjected to the downward and upward vertical forces, respectively. Fig. 4 (a) shows typical deformations of the connection at 4% drift. Obvious elongation of the SMA bolts on the top row can be found and the two groups of SMA washers are compressed to nearly flat shape, which allowed the deformation of the connection without stretching the HS bolts. When the loading is released to zero, the connection returns to nearly the original shape, and there is no visible residual deformation found in the main structural members, as shown in Fig. 4 (b).

The moment-plastic rotation curve of the specimen is presented in Fig. 3, where the moment is obtained by the product of \( P \) and \( L \) (1025 mm). The curve shows a flag shape in general and becomes stable gradually. Prior to 0.75% drift, no obvious hysteretic response can be observed. After 1% drift, the hysteretic response becomes significant. No failure of the connection occurred at 4%. Besides, it is notable that the moment of connection shows an increasing trend with the increase of the cyclic number. Moreover, the test curve shows a significant asymmetry, and the maximum moments \( (M_{\text{max}}) \) are +30.2 kN·m and -23.5 kN·m, respectively. Further investigation on the cause of the phenomenon is in progress.

(a) at 4% drift  (b) after unloading

Fig. 4 Deformations of the HS-SMA connection
3.2 Strain readings

The development of strain at critical locations including the end plate, the stiffeners and the beam flanges is monitored by the corresponding strain gauges, and the typical readings of strain gauges are summarised in Fig. 5. The beam flanges and its stiffeners are found to respond elastically during the test, while the end plate begins to yield after the drift exceeding 1%, and the strain reaches around 3200 microstrains at 4% drift.

![Fig. 5 Strain gauge readings in critical locations of the specimen](image_url)
3.3 Strength and stiffness

The initial stiffness of the connection can be obtained via dividing the connection moment by $\theta_c$ (Penar 2005). In this paper, the $\theta_c$ at 0.375% drift is employed to calculate the initial stiffness (Fang et al. 2014), which is equal to 9280 kN·m/rad. The ratio of the initial rotation stiffness of the connection to $EI/L$, where $L$ is 2050 mm (twice the span of the cantilever beam), is around 7.9. In other words, this connection belongs to the semi-rigid class according to the Eurocode 3 (EN 2005). As mentioned above, $M_{max}$ is found to be +30.2 kN·m and -23.5 kN·m, respectively in the test, and the ratio of $M_{max}$ to the plastic moment resistance of the beam ($M_{b,pl}$) is 0.8 and 0.6, respectively, which means that the connection can be classified to be partial-strength one (EN 2005).

3.4 Self-centring ability

The self-centring ability of the connection can be presented by the accumulated value of the residual deformation of the connection. In this paper, the residual plastic rotations of connection for the last cycle of each drift are employed to evaluate this important behaviour, as shown in Fig. 6 (a), where the percentage of the value of total plastic rotation at 4% drift is also summarised. It can be found that the total residual plastic rotation is less than 0.0004 rad, with percentages on the overall plastic rotation 1.06%. In other words, nearly 99% of the plastic deformation of the connection can be restored after unloading.

![Fig. 6 Residual deformation and EVD values of the HS-SMA connection](a) (b)

3.5 Energy dissipation ability

The energy dissipation ability of the connection can be evaluated by the equivalent viscous damping (EVD), $\xi_{eq}$, which can be calculated as follows (Speicher et al. 2011):
where $W_D$ is the amount of energy lost per cycle, which can be considered as the area of the corresponding hysteretic loop; $W_E$ is the amount of the energy absorbed in a linear system composed by the same maximum moment and maximum rotation. Fig. 6 (b) shows the EVD values of the connection (the values are calculated for the first cycle at each drift level). In general, $\xi_{eq}$ increases with the increase of the drift amplitude. $\xi_{eq}$ is minor, less than 1%, before 0.75% drift, which is consistent with the observation of slender hysteretic loops prior 0.75% drift in Fig. 3. After 1% drift, the hysteretic loops in Fig. 3 become significant and $\xi_{eq}$ increased from 1.54% at 1% drift to 8.54% at 4% drift.

4. CONCLUSIONS

As a continuation of the previous numerical investigation conducted by the co-authors, an experimental study is carried out to validate the feasibility of the HS-SMA hybrid connection. A full-scale test of an HS-SMA connection under cyclic loading is designed and conducted. It should be noted that the specimens are designed based on the experiences of previous studies and a larger ratio of $D_3/D_1$ (1.19) is employed to manufacture the SMA bolts to avoid a premature fracture.

It is found that the specimen is loaded up to 4% drift without failure and exhibits stable structural performance under cyclic loading. The moment-plastic rotation curve shows a flag shape in general. The maximum clockwise moment is found to be +30.2 kN-m, 80% of the plastic moment resistance of the beam. According to relevant specifications, the specimen with this novel connection can be classified to the SMF and DCH structures, respectively. Besides, during the entire test, the beam flanges and its stiffeners are found to deform in the elastic range. According to the Eurocode 3, this connection is found to belong to the semi-rigid and partial-strength classification, respectively. Moreover, the total residual plastic rotation of this connection is found to be less than 0.0004 rad, with percentages on the overall plastic rotation 1.06%. In other words, nearly 99% of the plastic deformation of the connection can be restored after unloading. As for the energy dissipation ability, the value of the equivalent viscous damping, $\xi_{eq}$, is found to be 8.54% at 4% drift. It is also worth noting that the SMA washers in the hybrid connection could not only protect the HS bolt from plastic deformation, allowing them to carry the shear action in the connection efficiently, but also could provide recentring driving force for the connection and play a role as an extra energy dissipation source.

In summary, the HS-SMA hybrid connection possesses an excellent self-centring ability, shear resistance, as well as reasonable energy dissipation capacity under seismic loading. More experiments and numerical study are currently in progress to further examine the structural behaviour of this type of hybrid connection. Application of
the connection in practical engineering can not only reduce the cost of post-earthquake repairing work but also be with great value for developing a new generation of sustainable building with self-adapted and self-recoverable structures.

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