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PRELIMINARY STUDY ON NOVEL BEAM-TO-COLUMN CONNECTION BASED ON SMA PLATE

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A novel beam-to-column connection equipped with shape memory alloy (SMA) plates has been proposed to realize resilient performance under low-to-medium seismic actions. In this conference paper, the detailed 3D numerical technique calibrated by the previous paper is adopted to examine the hysteretic behavior of the novel connection. A parametric study covering a reasonable range of parameters including the thickness of the SMA plate, friction coefficient between SMA plate and beam flange and pre-load of the bolt was carried out and the influence of the parameters was characterized. In addition, the effect of the SMA Belleville washer on the connection performance was also studied. The results of the numerical study showed that the initial connection stiffness and the energy-dissipation capacity of the novel connection can be enhanced with the increase of the thickness of the SMA plate. In addition, the initial connection stiffness and energy-dissipation behavior of the novel connection can be improved by increasing the friction coefficient or pre-load of bolts, whereas the increased friction level could compromise the self-centering behavior of the connection. The hysteretic curves of the numerical models of the connection also implied that the SMA washers may contribute to optimizing the connection behavior by increasing the connection stiffness and energy-dissipation capacity without sacrificing the self-centering behavior.

Keywords: Self-centering, SMA washer, Energy dissipation, Stiffness.

1 INTRODUCTION

It has been widely accepted that the commonly used steel moment-resisting frames (SMRFs) designed based on the current code-compliant methodology would exhibit non-ignorable residual deformation after subjected to design-based earthquake (DBE) (Civjan *et al.* 2000, Kunnath and Malle 2002). According to the FEMA P58 (2011), if the residual story drift of the structure exceeds 0.5% after the earthquake, it can be regarded economically undesirable to retrofit. The above-discussed economic loss underscored the urgent demand of adopting novel seismic strategies to enhance the structural performance with the expectation of robust strength/stiffness, controllable damage evolution mode, reliable construction art and low residual deformation.

After introduction of the post-tensioned (PT) technology to the concrete structure, it, subsequently, was extended to the SMRFs and other structural systems to improve their behavior by Ricles (2002), Christopoulos *et al.* (2002) and Garlock *et al.* (2003). Recently, much attention also has been paid into the engineering applications of the SMAs due to their two noteworthy characteristics, namely shape memory effect (SME) and superelastic effect (SE) (DesRoches *et al.* 2004). A batch of traditional connections, which was retrofitted by SAM bars with shape memory effect (SME) features has been tested by Ocel (2004). In light of the performance of practical connection types (e.g. extended end-plate beam-to-column connection), a series of test programs evaluating the cyclic performance of several connection types equipped with SMA-based devices were conducted (Fang 2014, Yam 2015, Fang 2017). According to the test observations and numerical parametric studies, a set of preliminary design considerations was systematically proposed. In addition, some new connection configurations integrating innovative SMA components (e.g. SMA Belleville washers, SMA ring spring system and SMA ring spring damper) were also preliminarily explored.

However, pre-stress loss and premature failure of steel strings may undermine the effectiveness of the PT function during the service period, especially when the high-level initial pre-stress is needed. On the other hand, for connections based on the SMA bars, apart from the relatively smaller stiffness, the premature fracture of SMA bars was also indicated in previous research (Fang 2014, Yam 2015, Fang 2017). Consequently, a completely new attempt of connection based on SMA plate is made in this paper and a feasibility study on this novel connection equipped with the SMA plates was carried out numerically with the aim of both enhancing seismic performance and reducing the probability of premature fracture induced by stress concentration. A parametric study covering a reasonable range of parameters including the thickness of the SMA plate, friction coefficient between SMA plate and beam flange and pre-load of the bolt was conducted. In addition, the SMA Belleville washers were also introduced to further optimize the connection behavior. Based on the above discussion, some design considerations are also given.

2 CONNECTION CONFIGURATION AND WORK MECHANISM

Figure 1(a) illustrates detailed diagram of the proposed exterior connection. The beam is connected to the column by two T-type connectors. The left end of SMA plate is installed between the webs of T-type connectors and top/bottom flanges of the beam, while the other side is fixed on the beam by high strength bolts. The SMA plate is fabricated with dog-bone shape. In this connection configuration, the following potential advantages should be shed light to: 1) the SMA plate can be free of uncertain shear-related premature damage due to the uneven deformation; 2) a tunable connection performance can be ensured by adjusting the pre-load in the bolts connecting SMA plate, T-type connector web and beam flange.

This novel SMA plate-based connection is proposed as a promising candidate with tunable connection performance for the structures. The deformation diagram and the idealized moment-drift hysteresis curves of the connection are shown in Figure 1(b) and Figure 1(c), respectively. In Figure 1(c), the expected response of the connection with and without bolt preload on the slotted side, are shown in red and blue loop, respectively. According to the Figure 1(c), the hysteresis response of the proposed connection exhibits the multi-linear characteristics for the case with bolt preload. In addition to the above desirable multi-linear behavior, the connection can almost return to original position due to the SE effect of the SMA material after unloaded.

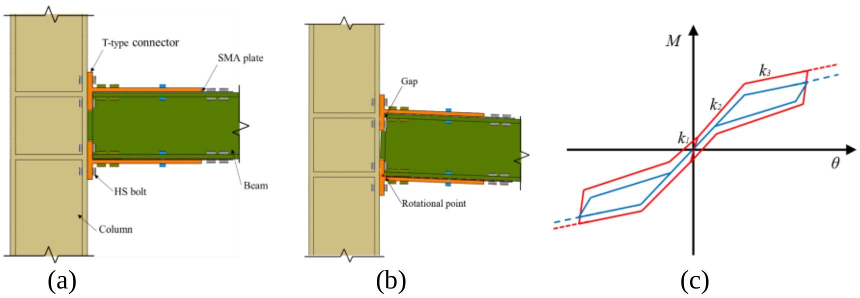


Figure 1. Connection configuration and response: (a) diagram of the proposed connection (b) diagram of the deformed connection (c) idealized moment-rotational-drift response of the connection.

3 NUMERICAL ANALYSIS OF THE CONNECTION

3.1 Modeling Strategy

To verify and better understand the seismic performance of the proposed connection, 3D FE model (Figure 2) based on the previous research was established (Wang *et al.* 2016 and Wang 2017). All structural members were discretized by solid element. High strength steel with nominal stress 690MPa was adopted. For the SMA plates, a built-in material model based on the Auricchio's approach was selected to simulate the superelastic mechanism of SMA. The associated key material parameters are given in the Table 1 and symbols are schematically marked in Figure 3.

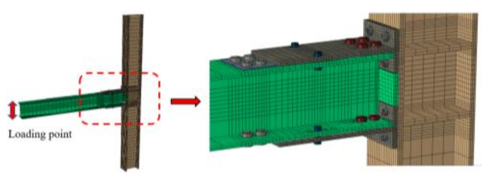


Figure 2. FE model of the proposed connection.

In this preliminary FE study, the dimensions of the beam and column were HN250×160×12×16mm and HN300×200×16×20mm, respectively. The lengths of the beam and column were 2000mm and 3000mm, respectively. The total length of the SMA plate was 547mm. The name convention for the specimen starts with the preload in each bolt, followed by the friction coefficient of the interface between the SMA plate and the beam and thickness of the SMA plate. The string'washer' is attached to the end of the name if the connection is enhanced by the SMA washer.

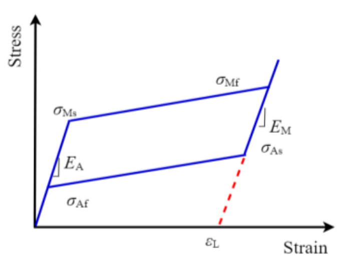


Figure 3. SMA definition.

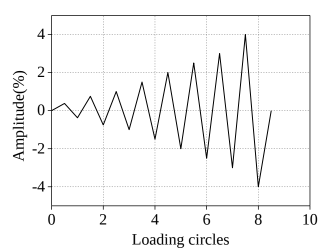
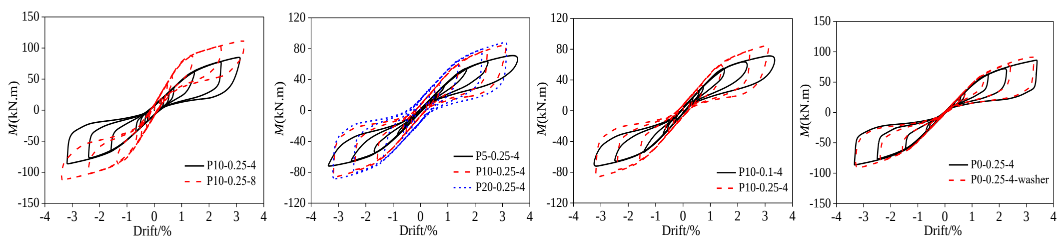


Figure 4. Loading protocol.

Table 1. The material constants of SMA used in FE analysis.

Material Constants	Value
Forward transformation stress in tension, σ_{Ms} (MPa)	350
Forward transformation stress in tension, σ_{Mf} (MPa)	600
Reverse transformation stress in tension, σ_{As} (MPa)	250
Reverse transformation stress in tension, σ_{Af} (MPa)	75
Poisson ratio at austenite state, ν_A	0.33
Poisson ratio at martensite state, ν_M	0.33
Maximum transformation strain, ε_L	0.04
Austenite modulus of elasticity, EA(GPa)	40
Martensite modulus of elasticity, EM(GPa)	40

The cyclic pushover analysis of the connection model was divided into two steps. In the first step, all the bolts were preloaded to a prescribed level of the bolt load. Subsequently, a concentrated cyclic load was applied at the beam tip under the displacement control. Figure 4 gives the loading protocol used in the FE analysis with the maximum displacement amplitude 2000×4%=80mm.



(a) thickness of the SMA plate (b) pre-load (c) friction coefficient (d) washer

Figure 5. Comparison of hysteresis curves of connection with varied parameters.

3.2 Numerical Results

Figure 5(a) shows the numerical results of the cyclic moment-rotational drift curves of the novel connection with different thickness of the SMA plate and same pre-load (e.g. 10kN). It was noted that the rotational stiffness and strength of the connection can be obviously enhanced by increasing the SMA plate thickness. Smaller residual deformation was observed for the specimen P10-0.25-8. Apart from that, due to the low-level friction between the SMA plate and the beam flange, although the first phase of the curve was relatively short, it was still robust enough to resist the lateral impetus. With the increase of the earthquake impetus, the phase transformation of the SMA plate was triggered, and then, the stiffness of the connection reduced rapidly with the aim of elongating the structural period to diminish the seismic response, while the energy absorbing ability was complemented by the SMA pseudo yielding mechanism.

To shed the light on the effect of bolt preload, three specimens with same parameters except for the preload were taken into considerations. The Figure 5(b) gives the comparisons of the cyclic response of each specimen. It was clearly seen that with the increase of the bolt preload, the strength and energy dissipation capacity of the connection were improved to a certain degree respectively, echoed by a fuller hysteretic curve. In addition, for the specimen with higher bolt preload, the first phase of connection was enhanced, and the connection can effectively provide the enough stiffness and strength to resist the service loads before the friction was overcome. However, this enforcement of the connection performance, on the other hand, jeopardized the self-centering behavior of the connection and the residual deformation became slightly larger.

Figure 5(c) depicts the comparison of the cyclic response between the specimens with different friction coefficient. In general, an expanded hysteretic curve was observed for the specimens with 0.25 friction coefficient, compared to the specimen with 0.1 friction coefficient. According to the Figure 5(b) and Figure 5(c), it can be concluded that effect of increasing the friction coefficient on the connection performance is similar to that of exerting higher preload to bolts. And although the connection behavior was reinforced when the larger friction coefficient was adopted, this improvement inevitably compromised the re-centering ability.

To better understand to what extent of the SMA washer devices can enhance the connection performance, Figure 5(d) shows that after installation of the SMA washer devices in the connection, the stiffness and strength of the specimen P0-0.25-4-washer were augmented, when compared to the specimen P0-0.25-4. In terms of the energy dissipation, the connection with SMA washer exhibited a slightly fuller cyclic loop. It can be attributed to that, the SMA washer under compression initially provides a certain stiffness to the connection, and after the phase transformation is triggered, then further optimizes the energy dissipation ability of the connection under the higher seismic impetus. Thus, installing the SMA washer is a promising strategy to further improve the cyclic behavior if needed, which should be further studied.

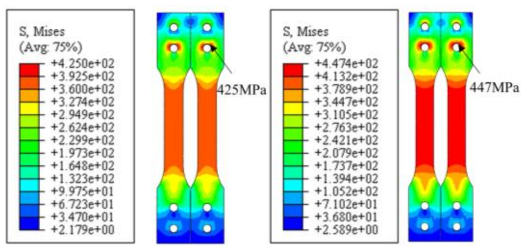


Figure 6. Comparison of stress contour of specimen P10-0.1-4 and specimen P10-0.25-4.

As described in section 2, the connection configuration based on SMA plate can effectively avoid the shear-induced damage caused by uneven deformation along the SMA bolts when the connection decompresses in previous research (Fang 2014, Yam 2015, Fang 2017). However, the stress concentration phenomenon may occur around the bolt shank and bolt hole wall if the bolt shank contacts the bolt hole to transfer the internal force, which may jeopardize the reliability of the bolted connection because the local-damage resisting ability of SMA plate has not been evaluated. To understand to what extent of the stress concentration around the bolt hole wall of the SMA plate when the connection decompresses, the contours of the SMA plate were extracted when the external connection moment was 60 kN.m for the specimen P10-0.1-4 and specimen P10-0.25-4, respectively, as shown in Figure 6. It was noted that, at the slotted side of the bolted connection, the stress around the SMA hole wall was higher than that in the reduced SMA segment, denoting the stress concentration. In addition, in terms of the other side of the bolted connection between the SMA plate and beam flange where the preload in each bolt is enough to ensure the friction connection, the stress concentration was almost avoided.

4 CONCLUSIONS

A preliminary study on seismic performance of the connection incorporation the SMA plate and friction mechanism has been carried out and detailed configuration is also given in this paper. The proposed connection can effectively avoid the shear-induced damage and can realize the tunable performance towards varying seismic demands. A wide parametric study on this connection has been carried out to explore effects of each on the connection performance after the modeling strategy was validated by the previous research. In addition, the SMA Belleville washers were also introduced to further optimize the connection behavior. Some design considerations are given below:

1. The flag-shaped hysteretic curves and multi-linear backbone curves are confirmed, which is desirable.
2. The higher level of the friction between the SMA plate and beam flange can enhance the initial stiffness and strength by extending the first phase the connection, while this optimization can jeopardize the self-centering behavior of the connection.
3. Stress concentration phenomenon at the slotted side of the bolted connection between the beam flange and SMA plate is observed.
4. SMA washer initially provides a certain stiffness to the connection, and after the phase transformation triggered, then further optimizes the energy dissipation ability of the connection under the higher seismic impetus, which is a promising strategy to improve the cyclic behavior if needed.

Acknowledgments

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