FEASIBILITY STUDY ON A NOVEL RE-CENTERING BEAM-TO-COLUMN CONNECTION WITH MULTI-STAGE ENERGY DISSIPATION MECHANISM

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Abstract

Novel beam-to-column connections sustaining negligible or no damage after earthquakes is an integral basis towards seismic resilient steel moment resisting frames. This conference paper proposes a novel beam-to-column connection to be used in steel moment resisting frames, and the hysteretic performance is expected to be characterized by satisfactory re-centering ability and multi-stage energy dissipation behavior. A hybrid damping mechanism is proposed to feed the seismic demands of earthquakes with varied intensities. The paper is commenced by introducing the detailed configuration of the connection. By incorporating super-elastic Shape Memory Alloy (SMA) material and post-tensioned high strength steel bars/strings concurrently, the energy dissipation and pre-stress level in high-strength steel bars/strings of the connection can be adjusted with sufficient flexibility. In particular, the pre-stress provided by pre-tensioned bars/strings may ensure sufficient stiffness of the connection to resist service loads (e.g. wind). The gap opening between the column and the beam may occur with the increase of incitation, while remarkable post-decompression rotational stiffness can be guaranteed to control the deformation development, accompanied by stable energy dissipation by offered by friction when subjected to from a frequently occurred earthquake (FOE) to a design-based earthquake (DBE). In a seismic event with higher intensity, the post-decompression stiffness further decreases owing to the “pseudo yielding” of SMA devices. Thus, the structure may be shifted to the longer period region, and the seismic demand may further decrease accordingly. Meanwhile, inception of inelasticity of SMA devices may contribute to hysteretic energy capacity of the connection. Based on a wise combination of the connection detail, it is hopeful to achieve fully re-centering behavior of the connection after rare earthquakes. To combat drawbacks of conventional post-tensioned connection in extreme case where the steel bars/strings may fracture, resulting in total resistance loss of the connection, special slotted bolted detail in the beam flanges allowing for formation of residual strength of the connection in the post-ultimate stage is proposed. The performance of the novel connection is examined using the finite models verified by test results. As a proof-of-concept study, cyclic analyses of prototype connections are performed, and the influential parameters are identified. The numerical results confirm that the proposed connection can achieve encouraging seismic performance, and is a promising candidate for seismic applications. Preliminary numerical results gleaned from the column removal scenario show satisfactory multi-hazard resistance of the proposed connection.

Keywords: resilient, shape memory alloy, re-centering connection, cyclic behavior.

1. Introduction

Although the current seismic deign criterions allow the structural engineers to explore the inelastic potential in structural members (e.g. beam end and panel zone), the exceedingly economic loss associated with repair of the damage on structural elements and subsequent downtime also drives the civil researcher community to seek more resilient structural systems [1-3]. Some researches have shown that it is economically undesirable to repair a damaged structure if the residual drift exceeds 0.5% after a ground motion [4]. In addition, post-earthquake investigations highlight the underling uncertainty of brittle fractures triggered by poor quality of welding for the fully-restrained steel connections [5]. The above-mentioned economic loss and uncertainty signal the urgent demand for adopting advanced seismic technology to enhance structural performance with the aim of robust strength, controllable damage, reliable construction art and negligible permanent drift.

Recently, some efforts have been put into self-centering structural systems where post-tensioned steel strings/bars were used as driving force to decrease the residual deformation in combination with supplemental energy-dissipation devices [6-11]. Post-tensioned steel connections were proposed as a promising candidate to gain the self-centering behavior. Among various configurations of PT connections, the essence of connection mechanism was to maintain the main structural elements (e.g. beam, column) in elastic state and restrict the inelastic behavior in easily replaceable elements, while the recovering force was provided by PT strings/bars running parallel to beams and anchored at column outer flanges. PT connections with steel angles [2, 9], friction devices [7], buckling-restrained bars [8], and web hourglass-shaped pins [11] were investigated. Also, the seismic performances of moment-resisting steel structures equipped with PT connections were evaluated when subjected to ground motions with various intensities [10]. Based on enormous analytical and experimental studies, the results showed that both the connection- and systems-level exhibited the flag-shaped hysterical loops with negligible residual drift and stable energy dissipation capacity.

Accompanied by the above efforts, a parallel attempt was also made to explore the potential application of shape memory alloy (SMA) in civil engineering [12-22]. A SMA is a class of metals with two noteworthy characteristics, namely shape memory effect (SME) and superelastic effect (SE). In particular, when SMAs deformed at a temperature above the austenite finish temperature A_f, the inelastic strain can spontaneously recover once unloaded, a phenomenon called superelastic effect (SE). On the other hand, the phase transformation from martensite to austenite starts upon heating the SMA above A_s (austenite start temperature) and finish at the A_f (austenite finish temporary) after unloading, resulting in recovering to initial shape, which is called the shape memory effect (SME) [12]. Owing to the unique phase transformation characteristics from austenite state to martensite state, SMAs have drawn much attention from the academia. The aforementioned SMA traits were desirable in developing the material-based self-centering concept for more resilient structures. Ocel [13] incorporated the SMA bars machined by SMA material with shape memory effect (SME) features into the traditional connections. The test results showed both excellent seismic performances and the capacity of rehabilitation with smaller residual deformation by heating the SMA bars above the transformation temperature. Abolmaali et al. assessed the seismic behavior of connections connected by T-stub connectors using the superelastic SMA bolts and revealed that the self-centering property was confirmed, while the unsatisfactory ductility was also identified, which may be attributed to the unreasonable design details of SMA bolts [14]. Later, a series of test programs evaluating the cyclic performance of several connection types equipped with SMA-based devices were conducted [18-20]. According to the test observations and numerical parametric studies, a set of preliminary design considerations were proposed. In addition, some new connection configurations integrated innovative SMA components (e.g. SMA Belleville washers, SMA ring spring system and SMA ring spring damper) were also preliminary explored.

Above all, a great progress has been made in developing resilient connections by either PT technology or utilizing of SMA-based devices to gain the high performance against the earthquake impetus. Comparing the two strategies, a relatively lager initial rotational stiffness of connection by PT technology is ensured, while the latter exhibits a semi-rigid connection rotational stiffness. Pre-stress loss and premature failure of steel strings, however, may undermine the effectiveness of the PT function during the service period, especially when the high-level initial pre-stress was needed. On the other hand, apart from the relatively smaller stiffness, the premature fracture of SMA bars was also indicated, which can be attributed to the inappropriate design details by [18-19]. This damage also could be induced by the concentration deformation with slightly curved shape for the gap forming. And other studies demonstrated that the shear behavior of SMA bars was not desirable and can extremely influence the SMA axial property [21-22]. Consequently, in this conference paper, a feasibility study on a novel re-centering beam-to-column connection combining the two strategies is carried out with the aim of enhancing the seismic performances by explicitly utilizing the advantages of the both. The paper commences demonstrating multi-stage energy-dissipation mechanism for the proposed connection, where PT strings are used as driven force to re-center and the SMA damping devices are considered as a supplementary damper only activated above the design-basis earthquake (DBE).

Subsequently, the numerical analysis is resorted and parametrically investigates the performances of the proposed connection. At last, based on the above discussions, some design considerations are also given.

2. Configuration and Multi-stage Energy Dissipation Mechanism

In line with the overall design concept of previous PT beam-to-column connections, Fig 1 illustrates detailed diagram of the proposed exterior connection. High strength steel bars/strings run parallel to neutral axial of the each side of beam web and are anchored in the column outer flange and beam end as a source of driven force. An additional reinforcement steel plate is introduced to enhance the robustness against the local stress concentration around the anchorage end. The beam is bolted to the column by special T-type connector with enlarging end which is used to connect the SMA damping device. In order to adapt to the gap opening of connection, the slotted holes are drilled in the beam flanges. Finally, the SMA damping device consisting of SMA bars is attached to the enlarging end of T-type connector and fixed in the beam to provide the supplementary energy-dissipation capacity. This above design has the following two advantages: 1) SMA bars can be free of the uncertain damage resulted from uneven curved deformation between connection surface duo to the gap opening; 2) Shear behavior of SMA bars is able to be eliminated with the definite function of dissipating energy and improving the post-decompression connection rotational stiffness. Apart from that, although the supplementary energy dissipation is introduced to the connection, there is no need of extra driven force to recover the inelastic deformation due to the superelastic effect of SMA. Therefore, self-centering force is only imperative to outrace the static friction between the T-type connector and beam flange.

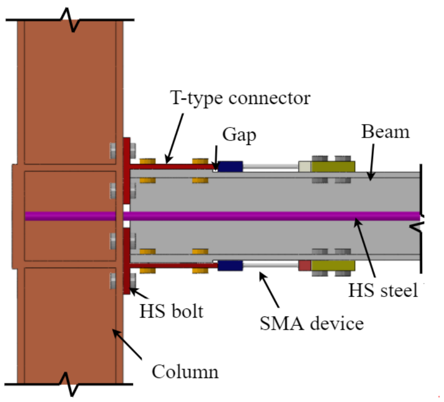


Fig 1. Diagram of the proposed connection

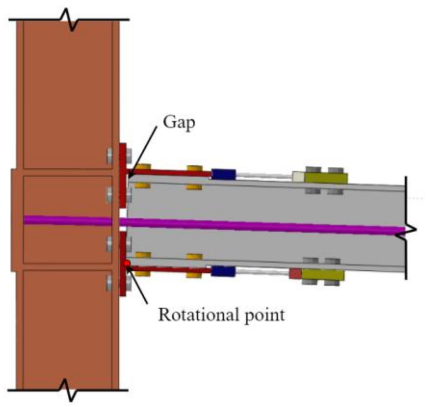


Fig 2. Diagram of the deformed connection

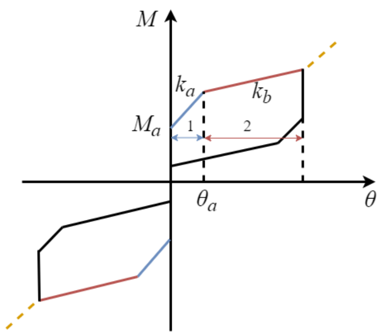


Fig 3. Idealized moment-rotational-drift response

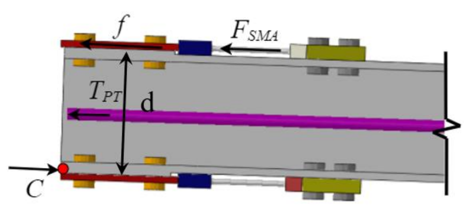


Fig 4. Horizontal force analysis

The novel connection is proposed with the aim of incorporating the respective advantages of PT technology and SMA-based connections. The deformation diagram and the idealized moment-drift hysteresis response of the novel connection are shown in Fig 2 and Fig 3, respectively. The sufficient initial stiffness which is equal to that of the fully restrained connection against the service loads (e.g. winds) is ensured by both the pre-stress in high strength steel bars/string and the static friction between T-type connectors and beam flanges. With the increase of the loads, once the decompression moment M_a (shown in Fig 3) is achieved, the connection gap commences forming. Compared with the previous PT connections, although the rotational stiffness (k_a) of the connection after decompression also experiences an abrupt drop, a slightly larger post-decompression connection stiffness still can be confirmed due to the contribution of axial stiffness of SMA bars, which is desirable to control the structural deformation under the design-basis earthquake (DBE). During this phase, all the energy is steadily dissipated by the friction mechanism. Subsequently, the post-decompression stiffness further decreases owing to the "pseudo yielding" of SMA device, while the energy dissipation capacity is complemented by triggering the inelasticity of SMA device, indicating that the structure may be shifted to the longer period region, and the seismic demand may further decrease accordingly under the maximum considered earthquake (MCE). Based on the above discussion, the multi-stage energy dissipation mechanism of connections can be reasonably obtained through activating the inelastic behavior of SMA device at a target drift by adjusting axial stiffness of SMA bars (e.g. geometry or material property). In addition, to overcome the drawbacks of the conventional PT connections in extreme case where the steel bars/strings may fracture, resulting in total resistance loss of the connection, a rigorous slotted length is designed in the beam flanges, which allow bolt shank to contact with the bolt hole wall of beam with the aim of exploring residual strength of the connection in the post-ultimate stage to resist the collapse. Meanwhile, SMA device also can be protected from damage by closing gap between the enlarging end of T-type connector and reinforcement steel plate in the beam end. In this preliminary FE study, the dimension of the beam and column is HN250×160×12×16mm and HN300×200×16×20mm, respectively. The length of the beam and column is 2000mm and 3000mm, respectively. The diameter and effective length of the SMA bar are 12mm and 160mm. The diameter of each PT bar is 25mm.

Fig 4 gives the horizontal force analysis of all components in the connection. Eq. (1) shows the decompression moment of connection.

$$M_a = 0.5dT + n_1 \eta F_b \tag{1}$$

Where d is depth of beam, T is the sum of initial PT force, n_1 is the number of the bolts on the beam flange, F is the pre-load force of each bolts and η is the coefficient of friction. Approximate Eq. (2) can be derived to calculate the post-decompression of connection rotational stiffness.

$$k_a = k_d^{\theta} + n_2 k_{SMA} d^2 \tag{2}$$

Where k_d^{θ} is the rotational stiffness of connection [9], k_{SMA} is axial stiffness of each SMA bar, n_2 is the number of SMA bars in each device. It should be noted that the contribution of T-type connector to the connection stiffness is not considered in the equation for the simplification. In addition, all the shear force in this connection is reliably transferred by T-type connectors.

3. Numerical analysis of the connection

3.1 Modeling approach

In order to verify and better understand the desirable performances of the proposed connection, a 3D numerous model based on the previous research [20] was established. The FE model took into all structural components into consideration, as shown in Fig 5. C3D8R solid element was used to mesh beam, column, T-type connector, and bolts, while C3D8 elements with hourglass control were adopted to mesh the SMA bars. The steel strings were discretized by the truss elements. For general contact pairs, 'hard contact' behavior with no penetration in the normal direction was assumed for all the potential contact pairs. A Coulomb friction model with a friction coefficient of 0.25 was set. 'Couple' constrains were utilized to model the corresponding boundary conditions and loading point.

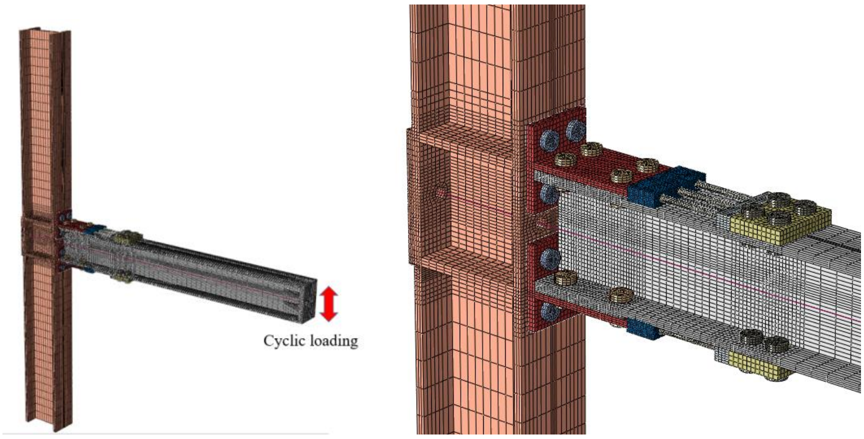


Fig 5. FE model of the proposed connection

A kinematic elastic-plastic stress-strain material model in conjunction with the von Mises yield criterion was used for steel components. High strength steel with nominal stress 690MPa was adopted. For the SMA bars, 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 include the Passion ratio at the at the austenite and martensite states (ν_A and ν_M), forward and reverse transformation stresses (σ_{Ms}, σ_{Mf}, σ_{As}, and σ_{Af}), Young's Moduli (E_A and E_M), and maximum transformation strain ε_L (material constants are given in the Table 1 and symbols are schematically marked in Fig. 6).

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, E_A(Gpa)	40
Martensite modulus of elasticity, E_M(Gpa)	40

The nonlinear analysis of the connection model was divide into tree steps. In the first step, all the bolts were preloaded to a certain level of bolt load. Subsequently, initial temperature filed method was used to exert the pre-stress in the steel bars. Finally, a concentrated cyclic load was applied at the beam tip under the displacement control. And Fig 7 gives the loading protocol used in the FE analysis with the maximum displacement amplitude 2000×4%=80mm.

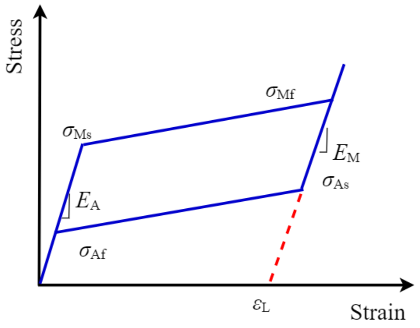


Fig 6. SMA definition

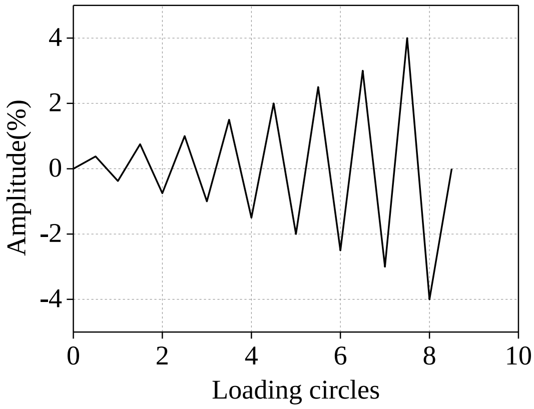


Fig 7. Loading protocol

3.2 Numerical results

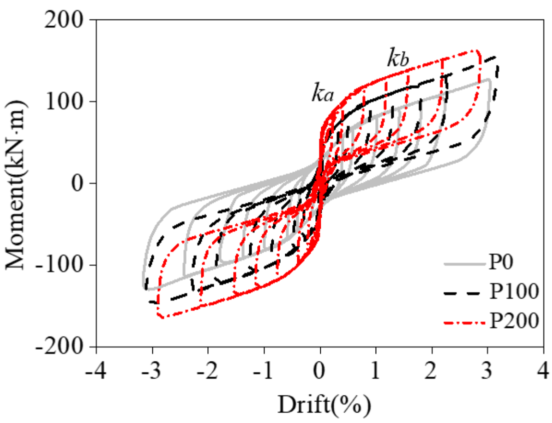


Fig 8. Comparison of hysteresis curves of connection with varied pre-stress levels

Fig 8 gives the simulation results of the moment-rotational-angle hysteresis curves of the novel connection with varied initial pre-stress force in each steel bar (e.g. 0kN, 100kN, 200kN). It was easily noted that typical flag-shaped cyclic response can be ensured when the initial pre-stress force reached the 100kN. Meanwhile, no residual rotational angle was observed. In addition, although no pre-stress force was exerted in the specimen P0, the connection response also exhibited flag-shaped at a certain degree. The infinite initial rotational stiffness of connections was guaranteed, followed by a slight larger post-decompression connection stiffness. After the activation of the phase transformation of SMA device, the post-decompression stiffness of the connection further decreased, suggesting that earthquake response can be mitigated by shifting the structure into a long period.

To illustrate the multi-stage energy dissipation mechanism, taking the specimen p200 into consideration, it was clearly found that before the connection rotational angel around 0.7%, only the friction behavior was triggered to provide the energy dissipation for the connection, while the stress-induced phase transformation of SMA device was not activated and still in elastic state as a complementary source of post-decompression connection stiffness. With the increase of the loading stage, once the SMA device entered into the inelastic state, the hybrid energy dissipation strategy can be triggered to enhance connection energy dissipation under the moderate-to-high earthquakes.

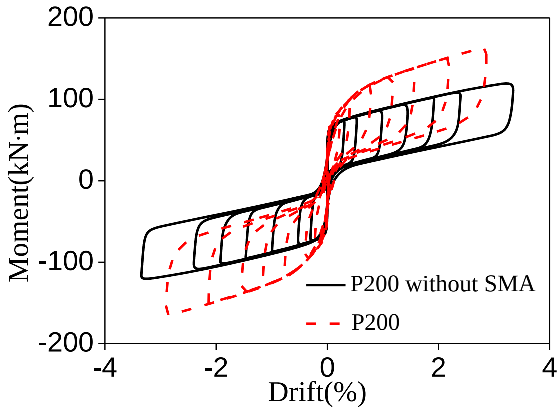


Fig 9. Comparison of the cyclic response of specimen with and without the SMA device

To demonstrate the advantage of the proposed connection optimized by the attached SMA device, Fig 9 gives the comparison of the cyclic responses of the specimen P200 with and without SMA device. What can be clearly indicated was that the multi-stage energy dissipation mechanism was confirmed by introducing the SMA device, while the specimen without SMA device, after the decompression of the connection, a relatively smaller rotational stiffness was observed in the rest of the loading process. A plumper hysteresis curves and robust resilience were achieved for the Specimen P200 with SMA device, suggesting the improved the energy performances (e.g. energy dissipation capacity and post-decompression behavior) after installation of the SMA device.

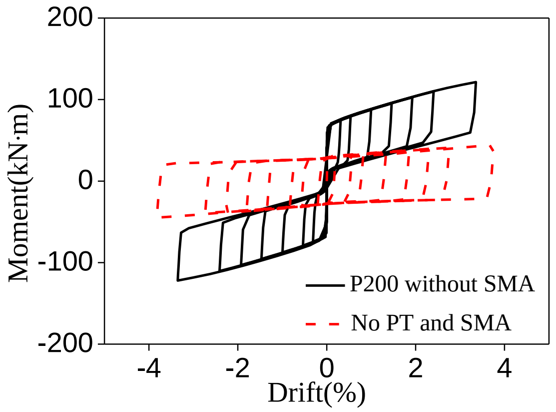


Fig 10. Comparison of the cyclic response of specimens

Fig 10 shows the comparison of the hysteresis curves between the specimen P200 without the SMA device and the corresponding specimen without both the PT steel bars and SMA device representing the conventional frictional connection. It was easily seen that a larger residual deformation was observed for the latter, indicating the necessity of much repair effort. The function of the pre-stress in steel bars was to force the hysteresis loops up and down separately to constitute the flag-shaped response with negligible residual deformation.

SMA device was designed to sustain the tension force till the stress-induced phase transformation, while it also had a risk of compression-induced buckling problem under the reversed loading. In light of this, taking the specimen P200 into account, the relationships of normal stress S33 and strain L33 in dog-bone part of each SMA bar were extracted from the FE analysis, as shown in the Fig 11. It was clearly descripted that the SMA bars can evenly sustain the external force and compression force was in a slightly lower amplitude free of bucking. Actually, the buckling effect can be eliminated during the design process. In particular, once the friction level was determined between beam flanges and T-type connectors, then the force each SMA bar undertook was explicitly derived to overcome the friction, which should be lower than the elastic Euler critical force of each SMA bar.

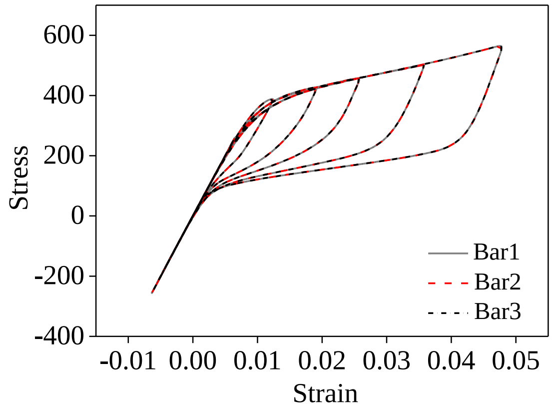
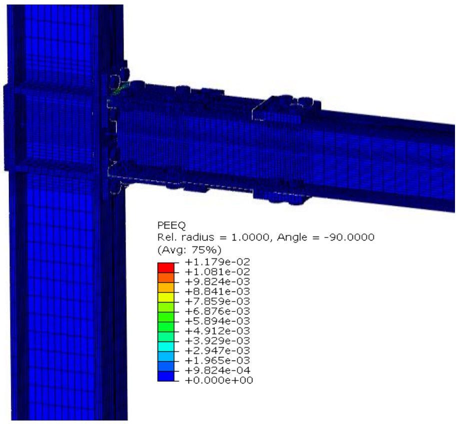
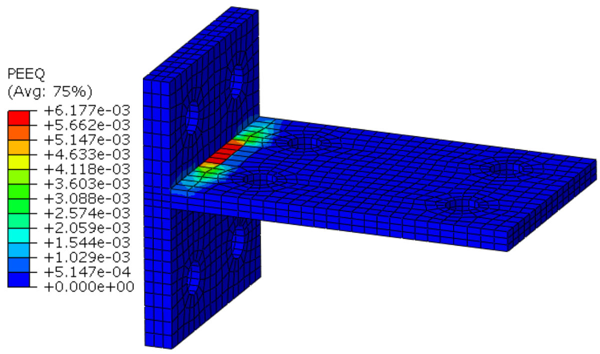


Fig 11. Relationships of stress-strain response of SMA bar

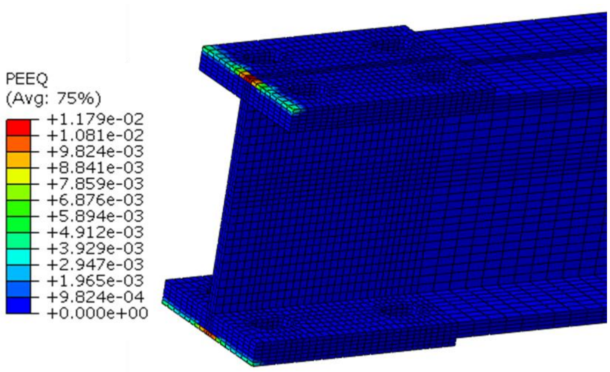
As described before, all the inelastic behavior of the proposed connection should be limited in the SMA device and friction mechanism, so the other main structural components were free of damage. And due to this new combination of the hybrid multi-stage energy dissipation mechanism, the novel connection can be brought back to the initial state without repair effort after an earthquake event. To verify this, Fig 12 presents the equivalent plastic strain contour of the each components. In addition, the typical strain history of some key areas are also given in Fig 13 (e.g. panel zone, the end of the T-type connector, and the beam end sustained the concentrated local stress).



(a) overall specimen

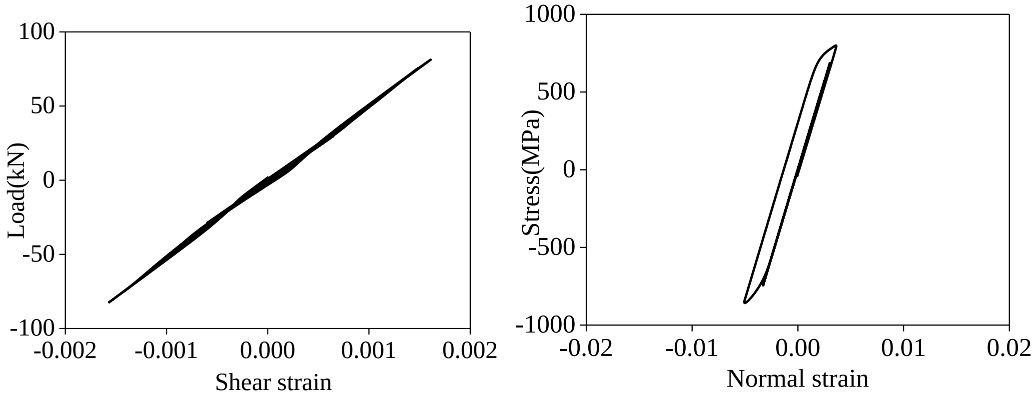


(b) T-type connector



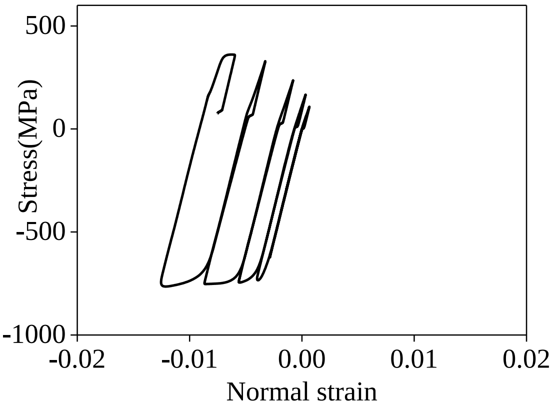
(c) Beam end

Fig 12. PEEQ of the specimen P200



(a) panel zone

(b) T-type connector end



(c) Beam end

Fig 13. Strain history of some key areas

According to the Fig 12, after the decompression of the connection, some areas subjected to local concentration stress had the potential of inelasticity, but the damage was minor and had the negligible influence on the global response of the connection. Fig 13 (a) shows the panel zone of the connection remained in the elastic state under the loading process, while the minor concentrated yielding parts were located at the end of the T-type connector and beam ends, which seemed inevitable due to the stress concentration. Some further investigations should be carried out to mitigate these damage and optimize the local response.

Base on the above discussion, the multi-stage energy dissipation mechanism of the proposed connection can be confirmed by introducing the hybrid damping strategies (e.g. friction and SMA device). All the inelastic response was restricted in the friction behavior and SMA devices, while only minor damage was observed in T-type connectors and beam flange ends due to the local stress concentration, which had negligible effect on the cyclic performance of the connection. A low level pre-stress force in steel bars was needed to bring the connection back to the initial position after a rare earthquake, suggesting that the proposed connection in this paper can be regarded as a promising candidate for the structural engineer to adapt to the higher seismic performance of owners.

4. Conclusions

A proof-of-concept study on seismic performance of the connection incorporating the multi-stage energy dissipation mechanism has been presented and detailed configurations were also given in this paper. The potential advantages of PT connection and SMA-based connection are explored. By combining the two type of connection strategies, a more desirable connection candidate has been validated by theoretical and FE analysis. Some preliminary findings are described below:

1. The decompression moment of the connection can be flexibly determined by adjusting the friction level and pre-stress force in steel bars, which can be sufficient to resist the service loads (e.g. winds).
2. A slightly larger post-decompression connection stiffness can be observed, which is attributed to contribution of the axial stiffness of SMA bars. This can be beneficial to control the structural drift under the low-to moderate earthquakes. And in this phase, all the input energy is stably dissipated by the friction mechanism.
3. Once the activation of the stress-induced phase transformation of SMA device, the connection stiffness further decreases under the maximum considered earthquake (MCE), which suggests the long period is guaranteed and earthquake responses can be reduced.

In addition, when the connection subjected to extreme case where steel bar fractures or super rare earthquake occurs, the bolt shank can be allowed to contact the bolt hole wall of beams to explore the residual strength of the connection by shifting the connecting into the conventional connection. This issue is theoretically considered and will be further investigated by test and FE analysis in the future.

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