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Self-centring behaviour of steel and steel-concrete composite connections equipped with NiTi SMA bolts

Cheng Fang [a,b], Wei Wang [a,b,*], Ce He [b,c], Yiyi Chen [a,b]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, Shanghai 200092, China
[c] Shum Yip East China Real Estate, 24 Jiangbian Road, Nanjing 210000, China

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This paper reveals the great potential of using NiTi shape memory alloy (SMA) bolts for self-centring connections against seismic action, with the main focus on the influence of composite slab systems on the connection performance. An experimental study on four full-scale specimens, including two SMA-based bare steel connections and two composite connections, is conducted. The results show that the steel specimens, classified as semi-rigid and partial-strength connections, exhibited satisfactory self-centring ability and ductility. For the composite specimens, due to the yielding of the reinforcement and metal deck, accompanied by cracking of the concrete slab, the self-centring ability is compromised to a certain extent. All the connections showed moderate energy dissipation capacity, with a stable equivalent viscous damping (EVD) of approximately 10% at large deformations. A comprehensive numerical study, employing an efficient yet simple way to capture the actual cyclic performance of the SMA bolts, is subsequently conducted, and the validated modelling approach is used to conduct a further parametric study, discussing the influences of bolt preload, reinforcement, metal deck orientation, and slab insulation. A preliminary design recommendation is also proposed based on the test data and the numerical study results.

1. Introduction

The extensive weld fractures of fully-restrained steel connections observed during the 1994 Northridge and 1995 Kobe earthquakes highlighted the critical role played by connection performance against seismic action. Subsequent investigations revealed that weld discontinuities, potentially resulting from the use of low-toughness welding electrodes with inappropriate welding process, mainly attributed to the poor seismic performance of the pre-Northridge welded connections [1]. Numerous research activities, including the well-known SAC Project [2,3], were carried out to investigate the reasons behind the extensive connection damage. The yield and failure mechanisms of various connection types were examined in detail, leading to the development of a number of pre-qualified fully-restrained and partially-restrained connections for practical use [3]. While these connections were proved to exhibit sufficient strength and ductility against design seismic action, these objectives are realised at the cost of significant structural inelastic/permanent deformations. Some studies suggested that repairing damaged structures is uneconomical if the residual story drift is greater than 0.5% after earthquakes, and as a result the structures may need to be demolished [4]. Even if the affected structures are repairable, the downtime inevitably leads to the necessity of arranging temporary shelter facilities for victims. One possible solution to address this issue is incorporating the idea of 'self-centring' in seismic design of structural systems. The core intention of self-centring design, under an idealised situation, is to eliminate the post-earthquake permanent deformations of the structures, hence minimizing repair work. To this end, structural engineers and researchers have been exploring new self-centring design concepts, among which endowing beam-to-column connections with self-centring abilities has been considered as one feasible strategy.

Post-tensioned (PT) steel connections and the associated sub-frames were proposed as an attempt to achieve self-centring connection response [5–7]. With the restoring force provided by the post-tensioned bars/cables along the beam length, the gap opening between the beam end and the column face can be closed upon seismic load removal, and additional energy dissipation devices and members could be used in combination [8]. A parallel effort

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China.
E-mail address: weiwang@tongji.edu.cn (W. Wang).

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was made to utilize nickel–titanium (NiTi) Shape Memory Alloy (SMA) components for achieving self-centring connection response. Attributing to the phase transformation of the material, SMAs are well-known for their shape recovery abilities after undergoing large deformations [9–12]. The shape recovery mechanism could be promoted either spontaneously or by temperature increase. The former occurs at the austenite state (at relatively high temperatures) and the latter happens at the martensite state (at relatively low temperatures), corresponding to the Superelasticity Effect (SE) and Shape Memory Effect (SME), respectively. The use of SMA components causes no extra compressive force to the steel beam (thus preventing early local flange buckling), and the SMA solution might also have the advantages of easy installation and compact size. Although the cost of material is still relatively high compared with other constructional materials, the price has decreased significantly over the past two decades.

Considering that ductility and energy dissipation demands of structures are most important, a series of SMA-based connections have been developed and examined where the SMA is the damage fuse and main provider of energy dissipation such that remaining members are damage free. Abolmaali et al. [13] revealed that T-stub connectors using superelastic SMA bolts could exhibit good self-centring properties, although the ductility was unsatisfactory due to inappropriate bolt detailing design. Ocel et al. [14] and Speicher et al. [15] further verified the feasibility of equipping shear tab steel connections with SMA tendons/bolts, where encouraging self-centring performance with moderate energy dissipation ability was observed for those connections. The authors of this paper and co-workers [16–19] launched a series of test programs assessing the cyclic performance of several practical SMA-based steel connection types. Based on the test observations and additional parametric studies, a set of preliminary design rules was proposed. Some new connection types incorporating innovative SMA components, including SMA Belleville washers and SMA ring springs, are also under development [20–22].

It can be clearly seen from the literature that great progress has been made in the research and improvement of SMA-based self-centring connections, and a good understanding has been gained at both material property and connection performance levels. However, the focus of the existing studies was mainly on SMA-based bare steel connections, whereas the influence of the slab system has not been studied in detail. Steel-concrete composite flooring systems, typically consisting of steel beams, cast-in-place concrete, shear studs, metal decks, and steel reinforcement, are mainstream structural forms for steel moment frame buildings. Due to the gap opening-and-closure response of the connections under seismic actions, incompatibility between steel and concrete can be induced at the connection zone, and the presence of the slab could affect the self-centring ability of the connections. It is worth mentioning that the same issue also exists in PT connections, and some measures have been considered to mitigate this incompatibility effect [23,24]. This paper provides further insight into the influence of beam-slab interaction on the connection performance. A total of four full-scale connections are tested in this study, followed by a numerical study which comprehensively discusses the influences of varying bolt and slab details. A preliminary design recommendation is also proposed based on the test data and the numerical study results.

2. Test program

2.1. Test specimens

A total of four full-scale specimens were tested in the current experimental program, and the basic geometric configurations are illustrated in Fig. 1(a). The main considered parameters were bolt diameter and connection type (i.e. steel or composite connection). Extended end-plate connections were employed as the main connection type, where the SMA bolts were installed through the entire cross section of the column. The thickness of the end-plate was 20 mm, and according to the relevant design guidance [25], the end-plate conforms to the 'thick-plate' criterion, i.e. no plastic deformation was expected. Specimens S-10 and S-16, which were steel connections, were equipped with four rows of SMA bolts (eight bolts in total) with the shank diameter of 10 mm and 16 mm, respectively. For the composite connections, i.e. specimens C-10 and C-16, their steel parts were identical to specimens S-10 and S-16, though a composite concrete slab was present. Each specimen represented a cantilever sub-structure consisting of a built-up H300 × 300 × 16 × 24 steel column, a built-up H170 × 100 × 12 × 14 steel beam (with or without the composite slab), stiffeners for the beam and column, and the associated connection zone. The same beam and column sizes were considered for the four specimens, and these steel members were designed to remain elastic (but were not reused) during the entire loading procedure. It is worth mentioning that the connection details considered in this proof-of-concept study do not necessarily represent the actual connections in practice. In this study, the connection shear resistance was adequately provided by friction (between the end-plate and column flange), but in actual design, seating brackets may be used to prevent steel beams from falling down at large connection deformations. Alternatively, the SMA bolts could also be used in shear-tab connections. A parallel study has been conducted by the authors and co-workers looking into the behaviour of such connections, and the test results have been published in a separate paper [19].

For the two composite connections, a composite floor slab with a depth of 101mm (51 mm deep ribs) and width of 900 mm was added to the steel sub-frame system. The slab system consisted of a continuous 1 mm-thick ribbed metal deck, with the rib direction (metal deck orientation) perpendicular to the beam axis. Continuous reinforcement of Φ6mm at 200mm spacing in the longitudinal direction and at 150mm spacing in the transverse direction was adopted to limit concrete cracking. Single line 80 mm-long, 19 mm-diameter headed shear studs were welded to the beam top flange to provide necessary composite action. With the metal deck acting as a permanent formwork, C20/25 (nominal cube strength = 25 MPa) concrete was continuously poured.

Grade Q345 steel (nominal f_y = 345 MPa) was ordered for the steel members including the beams, columns, stiffeners, and end-plates. The coupon test results, based on the average value from three coupons taken from each key location, are given in Table 1. The testing procedure conformed to BS EN ISO 6892-1:2009 [26]. Compressive tests on three 150 mm concrete cubes were conducted at the day of test, and the average cube strength $f_{cu,test}$ was 27.7 MPa. Commercially available NiTi (49.2 at.% Ti – 50.8 at.% Ni) hot-rolled SMA bars, with the raw diameters of 16 mm and 22 mm, were employed for the test specimens. Per information form the material supplier, the nominal austenite start temperature A_s is $-10\,°C \sim -5\,°C$ for the as-received raw bars. The 16 mm and 22 mm diameter raw bars were heat treated at 400 °C for 35 minutes and 45 minutes, respectively, and then water quenched. After heat-treatment, the bars were machined to the bolt form with the shank diameter of 10 mm or 16 mm, as detailed in Fig. 1(a). Some of the bars were also machined to dog bone shapes for material testing. The dog bone specimens were tested at room temperature under cyclic tensile loading with a strain rate of 0.0005/s. The peak strain of each cycle was incremented by approximately 1% strain until 6% strain, and this was followed by an extra loading cycle with a 7.5% peak strain. The typical