Journal of Constructional Steel Research 104 (2015) 177–192

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Numerical study and practical design of beam-to-column connections with shape memory alloys

Michael C.H. Yam [a], Cheng Fang [b,c,*], Angus C.C. Lam [d], Yanyang Zhang [a]

[a] Department of Building & Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China
[b] Department of Structural Engineering, School of Civil Engineering, Tongji University, Shanghai 200092, China
[c] School of Civil Engineering & Geosciences, University of Newcastle, Newcastle upon Tyne, NE1 7RU, UK
[d] Department of Civil & Environmental Engineering, University of Macau, Macau SAR, China

ARTICLE INFO

Article history:
Received 19 March 2014
Accepted 12 October 2014
Available online 31 October 2014

Keywords:
Shape memory alloy (SMA)
Extended end-plate connection
Recentring
Numerical study

ABSTRACT

This paper reports a comprehensive numerical study on end-plate beam-to-column connections equipped with NiTi shape memory alloys (SMAs). The numerical modelling strategy is first validated through comparisons with seven full scale tests conducted by the authors. The FE predictions correlate well with the test results, especially in terms of the deformation mode, strain reading, moment–rotation response, residual deformation, and equivalent viscous damping. Following the validation study, a parametric study is performed considering the effects of bolt layout, bolt length/diameter, beam-to-connection strength ratio, end-plate thickness, column web panel deformation, and shear resisting mechanism. In order to overcome a major issue identified from the parametric study, i.e. shear slippage, an improved HS-SMA hybrid solution is proposed. One of the novel concepts is the employment of HS bolts in collaboration with SMA Belleville washers, where the latter are used to absorb the bolt row deformation, to enable connection recentring, and to offer supplementary energy dissipation. A detailed FE model is established to confirm the feasibility of the HS-SMA hybrid connection, and an analytical model is also developed for normal design of such connections. A set of design rules for practical use are also proposed, and the required future studies are finally identified.

1. Introduction

NiTi shape memory alloys (SMAs) are nowadays promising functional materials used in many practical and research fields due to their two unique properties, namely, shape memory effect (SME) and superelastic effect (SE) [1]. The shape memory effect is featured when the NiTi SMA is deformed in its martensitic form. In this case, residual deformation is induced upon unloading but can be recovered through subsequent heating. The superelastic effect occurs when the NiTi SMA is deformed in the austenitic form, and the deformation can be recovered spontaneously upon unloading. Both effects have found their potential applications, but in the field of civil engineering (particularly in the area of seismic engineering), the superelastic effect seems to attract more attention due to the inherent characteristics of hysteretic damping and spontaneous recentring which can be utilised more conveniently. Over the last decade, engineers and researchers have been attempting to design various superelastic SMA-based seismic resisting devices and components (especially base isolations and dampers) to suppress the structural vibration or damage caused by earthquakes [2].

The community of seismic engineering has been exploring new design philosophies for connections that play a critical role in mitigating structural damages under seismic actions. Prior to the 1990s, fully restrained welded beam-to-column connections were widely used for steel moment resisting frames. However, as those connections failed extensively in a brittle manner in the Northbridge earthquake in 1994 and later in the Kobe earthquake in 1995 [3,4], a worldwide concern on seismic resisting design of beam-to-column connections has been initiated, and in particular, the critical issues such as ductility, energy dissipation, and post-hazard repair effort have been brought back to the fore. The cyclic responses of a wide range of connection types have been revisited, and more recently, some innovative connection types utilising smart materials to cater for specific functions such as recentring have also been promoted and largely driven by the performance based design framework which tends to significantly broaden the seismic design targets. Among various appropriate material candidates, NiTi superelastic SMA is considered as one of the most encouraging solutions due to their spontaneous recentring characteristic and moderate energy dissipation ability.

The initial study on recentring and energy dissipating connections can be traced back to the idea of using post-tensioned cables [5]. Approximately a decade ago, the potential of NiTi SMA for fulfilling the same function started to be considered as an alternative strategy, and experimental studies have been performed on this front. Ocel

* Corresponding author. Tel.: +86 (0)21 65983894
E-mail addresses: perfan@163.com, cheng.fang@ncl.ac.uk (C. Fang).

http://dx.doi.org/10.1016/j.jcsr.2014.10.017
0143-974X/

et al. [6] conducted two proof-of-concept tests on martensitic SMA-equipped shear tab steel connections, utilising the shape memory effect (SME) of the tendons via heating. The connections exhibited good energy dissipation, and more than half of the residual rotation was recovered after heating. Through performing additional tests on similar connection types but with superelastic/austenite SMA tendons, good spontaneous recentring abilities were observed by Penar [7]. Good recentring and energy dissipation were also found in the SMA bolted T-stubs conducted by Abolmaali et al. [8], but early bolt fracture has been identified as an important issue. DesRoches et al. [9] and Ellingwood et al. [10] studied the overall response of structures using SMA recentring connections, and the peak and residual inter-storey drift demands were discussed. Speicher et al. [11] further proved the efficiency of using SMA tendons for shear tab connections through undertaking four more physical tests. It was found that the austenitic SMA tendons were effective in facilitating recentring, and the specimen using the martensitic SMA tendons could recover 75% of the residual deformation upon heating. With the emerging positive test outcomes, the feasibility of their future application is envisaged.

However, major research efforts on SMA connections have been devoted to their structural behaviour, but the issues of installation complexity and floor-slab interference are sometimes overlooked. To enable ease of construction and to alleviate floor-slab interference, another type of proof-of-concept recentring connections, namely, extended end-plate connections with SMA bolts, has been investigated by the authors [12]. The idea was first proposed by Ma et al. [13], where the high strength (HS) bolts in conventional end-plate connections were considered to be replaced by superelastic SMA bolts, such that the ductility and energy dissipation demands could be accommodated by the deformation of the SMA bolts. One of the advantages of the design philosophy was that the remaining steel components could behave elastically with no permanent deformation, and as a result no or minor repair work may be required after earthquakes. To further assess the feasibility of the new concept, seven full scale tests have been conducted by the authors [12]. The tests showed encouraging cyclic responses in terms of recentring ability, hysteretic stability, and energy dissipation. However, some issues such as ductility, which was found to be affected by SMA bolt detailing, were also exposed. As limited test parameters were considered in the test programme, further studies are required aiming for a more comprehensive understanding of such connections and a detailed set of design guidelines available for practical use. Towards this end, detailed FE analysis are carried out in this study, which takes an in-depth look into the issues of bolt geometry/layout, beam behaviour, end-plate behaviour, column behaviour, and shear resisting mechanism. Through modifying the original test connections serving as prototypes, more practical SMA-based end-plate connections are proposed and carefully examined in this paper. Based on both numerical and experimental results, a design recommendation on SMA equipped end-plate connections is proposed, and further required work is also identified.

2. Tests performed by Yam and colleagues [12]

2.1. Test programme

A total of seven full scale tests on extended end-plate steel connections with four rows of SMA bolts have been conducted. The main test parameters were bolt length (190 mm, 240 mm, and 290 mm), bolt diameter (10 mm and 16 mm), and bolt arrangement. The test setup is shown in Fig. 1(a). Thick block washers were used to increase the SMA bolt lengths. Except for one of the specimens, the sizes of the beam and end-plate were selected to ensure that they remained in the elastic range during the loading process. Additional stiffeners were applied to further strengthen the end-plates. Each specimen was designated according to the bolt geometric configurations. The specimens in this paper are presented in the form of bolt Diameter–Length and connection Height, e.g. D10–L240–H210, where H is the distance between the two external SMA bolts (row 1 and row 4 bolts). Details of the specimen dimension and bolt layout are reproduced in Table 1 and Fig. 1(b).

A double action hydraulic load jack was used to apply the cyclic point load at the beam tip. A preload of 65% of the yield strength (forward transformation stress) was applied to all the SMA bolts in order to improve the recentring ability and also to ensure a sufficient initial friction between the end-plate and the column flange face. This friction was considered as the main shear force resisting mechanism for the test specimens. After bolt pre-loading, the cyclic load was applied according to the SAC project recommendation on loading protocols [3,4]. More details of the test programme can be found in [12].

2.2. Brief description of test results

The hysteretic responses of the seven test specimens can be typically presented by moment–plastic rotation curves, as shown in Fig. 2. The plastic rotation was obtained by deducting the elastic deformation of the beam from the overall drift (over drift = beam tip displacement / cantilever length). In general, the SMA connections showed recognisable flag shape hysteretic responses, and the overall deformation was mainly contributed to by the connection zone. The recorded initial stiffness and maximum bending moments indicated that the specimens were mainly semi-rigid and partial strength connections, except for specimen D16–L190–H210 which was a rigid/full strength connection. The maximum bending moment varied from 30 kNm to 90 kNm, depending on the bolt diameter and arrangement. For most connections, very good recentring properties were observed, and moderate energy dissipations were shown. The strain gauge readings confirmed that the main steel members were within the elastic range. The equivalent viscous dampings (EVDs) ξ_{eq} for the connections at 3% drift were generally at a level of 12%–14%, and the values tended to increase with increasing drift level. For some connections, however, bolt fracture occurred at the drift levels of 2% to 3%. This unexpected early fracture, which occurred over the threaded bolt cross-section only (as shown in Fig. 1(a)), was due to the low net threaded-to-shank diameter ratios D_3/D_1 (1.02 and 0.97 for the 10 mm and 16 mm SMA bolts, respectively). As other independent studies [7,11] showed high ductility behaviour of SMA bars with a net threaded-to-shank diameter ratio of around 1.4, it is therefore reasonable in future studies to anticipate improved ductility if sufficient threaded-to-shank diameter ratios are designed for the SMA bolts.

3. Finite element analysis of test specimens

3.1. General

Although full-scale physical tests can provide a reliable insight into the behaviour of the SMA connections, they are quite expensive and time consuming, and are less flexible for parametric studies. Therefore, the development of numerical modelling can be used as an efficient complementary investigation. In addition, for the tests conducted by the authors, the early bolt failures in some connections prohibited a complete understanding of their hysteretic response. The behaviour beyond bolt failure can be reflected by the corresponding numerical models. In this section, the numerical modelling strategy for simulating the SMA connections is elaborated. The test results of the seven specimens are used to validate the numerical models. The general nonlinear finite element (FE) analysis package ABAQUS [14], which is capable of simulating both material and geometric nonlinearities, is used for this purpose.

3.2. Finite element model

All components of the test specimens, including the SMA bolts, beams, end-plates, stiffeners, and columns, were simulated with 3-D