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Seismic performance of steel moment resisting frames utilizing superelastic shape memory alloys

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ABSTRACT

Steel structures dissipate the seismic energy through steel yielding, which results in residual deformations. Although conventional earthquake-resisting structural systems provide adequate seismic safety, they experience significant structural damage when exposed to strong ground shaking. Seismic residual drifts complicate the repair of damaged structures or render the structure as irreparable. Therefore, systems that can minimize the seismic residual deformations are needed. Superelastic shape memory alloys (SMAs) have the ability to undergo large deformations and recover all plastic deformations upon unloading. Their utilization in steel structures can significantly reduce seismic residual deformations, which will facilitate post-seismic retrofitting. Although the literature provides few research data on using SMA in steel beam-column connections, previous research did not address their optimum use. This paper identifies the required locations of SMA connections in a typical steel moment resisting frame to enhance its seismic performance in terms of maximum inter-storey drift, residual deformations, and damage scheme.

1. Introduction

Structural steel is widely used in moment resisting frames of mid- and high-rise buildings. Modern code provisions categorize buildings according to their configurations, structural systems, materials and construction details [1–3]. A structure is assumed to behave in a ductile manner if it can experience large inelastic deformations without significant degradation in strength. Steel moment resisting frames are one of the popular seismic load resistance systems because of their ductility. During a seismic event, they are expected to experience large inelastic deformations, while maintaining the life safety level for the occupants. Plastic hinges are expected to form in the beams, which may exhibit large yielding deformations leading to localized damage in the floor slabs and columns. Those yielding deformations are not recovered after the seismic event, which results in permanent residual deformations.

Researchers are innovating to find design solutions that minimize the seismic residual deformations. Special post-tensioned partially restrained connections were designed to provide recentering capability after a seismic event [4–6]. Shape memory alloys (SMAs) had also widely attracted the attention of researchers in recent years because of their self-centering capability as well as energy dissipation features. Nickel Titanium (NiTi) SMAs were the most researched [7]. The two fundamental and characteristic properties of SMA are: shape memory effect (SME) and superelasticity (SE). SME is the ability of the material to recover from large mechanically-induced strains via moderate increase in its temperature. SE is the ability of the material to support relatively high inelastic strains and return to its original shape upon load removal.

Ocel et al. [8] tested an external beam-column connection that utilized martensite SMA rods. The connection showed high energy dissipation, large ductility and no strength degradation up to 4% drift level. The connection was also able to recover 76% of the experienced drift when the SMA tendons were heated. Ma et al. [9] investigated the behaviour of extended end-plate connections consisting of long shank Nitinol superelastic SMA bolts, continuity plates, beam flange ribs and web stiffeners using a 3D finite element model. The connections experienced cyclic elongations of the SMA bolts, however the traditional beam local buckling was avoided. The deformations of the SMA bolts were recoverable upon unloading. Ma et al. [10] conducted a quasi-static test of an extended end-plate connection utilizing long shank SMA bolts. The connection exhibited high deformation capacity with maximum inter-storey drift (MID) angle beyond 0.02 rad. Sepúlveda et al. [11] tested a connection that utilized 3 mm-diameter copper-based (CuAlBe) SMA bars. The proposed connection experienced self-centering behaviour, dissipated moderate amount of energy, and showed no strength degradation up to 3% drift ratio. Speicher et al. [12] tested four half-scale interior beam-column connections that utilized steel tendons, superelastic NiTi SMA tendons, martensitic NiTi SMA tendon, or combination of superelastic NiTi tendons and aluminum tendons. The superelastic

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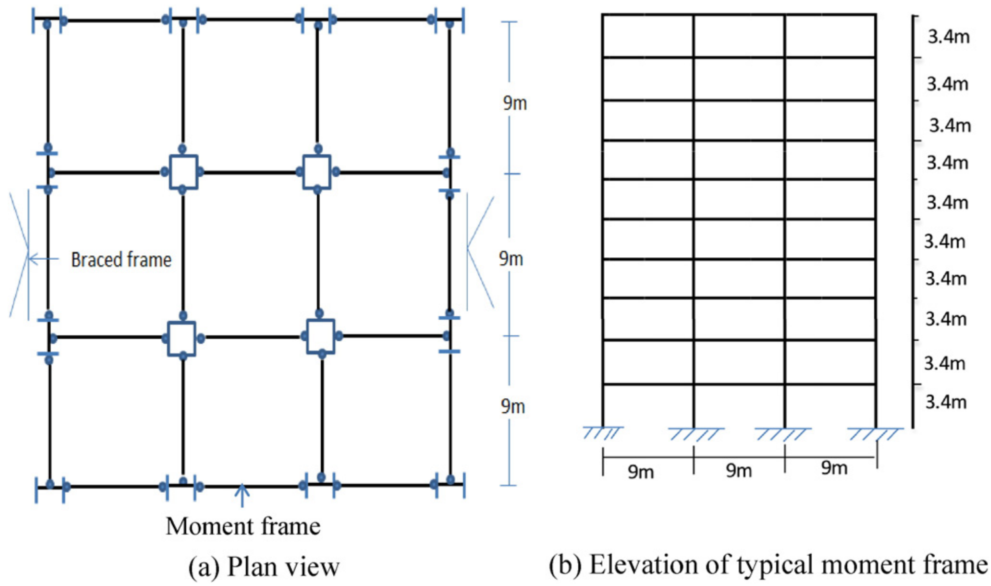

Fig. 1. 10-Storey building [23].

NiTi SMA connection showed significant recentering capability, recovering a large portion of the post-elastic drift compared to the other three connections. DesRoches et al. [13] studied the seismic performance of steel moment resisting frames with SMA bars at the beam to column connections. Two steel frames were selected: low rise (three-storey) frame and medium rise (nine-storey) frame. All the beam-column connections were assumed to utilize SMA bars. Nonlinear time history analyses showed that martensitic SMA connections are most effective in controlling MID demands whereas superelastic SMA connections are more effective in controlling maximum residual inter-storey drift (MRID) demands. Further, probabilistic seismic demand assessment (PSDA) was performed by Ellingwood et al. [14]. The hazard curves showed that the benefits of incorporating SMA connections depend on the seismic demand level. Researchers had also investigated the seismic performance of steel and RC frames equipped with SMA braces [15–17]. The conventional steel bracing system has limited ductility and energy dissipation due to buckling of the braces, and their asymmetric behaviour [18]. McCormic et al. [17] assessed the performance of steel braced frames equipped with superelastic SMA braces. The MRID was limited following an earthquake due to the recentering capability of the braces. Kari et al. [19] conducted a numerical study to investigate the benefit of using combination of buckling restrained braces and SMA braces for new designs as well as retrofitting purposes. Results revealed that, with the proper configuration, residual and inter-storey drifts can be minimized. Antonio et al. [20] conducted shake table tests to assess the effectiveness of seven different passive and semi-active energy dissipating braces (EDBs). It was concluded that EDBs consisting of both SMA and visco-elastic damping material lead to recentering of the gravity load resisting system at the end of a seismic event with the added advantage of higher energy dissipation because of the visco-elastic material. Miller [21] investigated the seismic behaviour and performance of self-centering buckling-restrained braces (SC-BRBs) that utilized SMAs. The SC-BRBs consisted of a typical BRB

Table 1
Limiting FID (%) for different floors of the 10 storey frame.

Storey	1	2	3	4	5	6	7	8	9	10
Proposed FID (%)	2.38	31.1	28.6	29.4	27.7	30.7	37.9	29.9	31.2	50.6

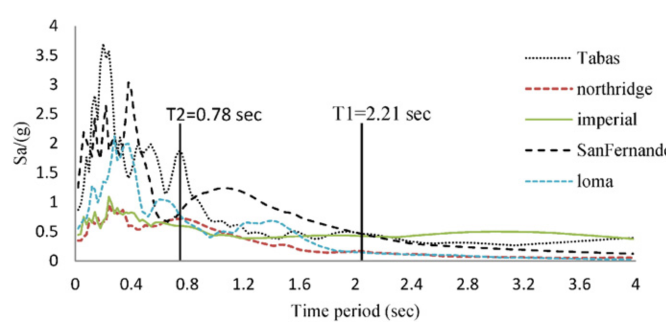

Fig. 2. Elastic response spectral acceleration for horizontal seismic component.

Table 2
Characteristics of ground motions.

Earthquake	Date m/d/yr	Ms magnitude	Station	PGA (g)
Northridge	01/17/1994	6.7	Arleta-Nordhoff	0.344
Imperial Valley	10/ 15/ 1979	6.9	El Centro Array #6	0.439
Loma Prieta	10/ 18/1989	7.1	Capitola	0.529
Tabas	09/16/1978	6.9	Tabas	0.852
San Fernando	02/02/1971	6.6	Pacoima dam	1.23

Table 3
MID and MRID of steel frame (Frame 1).

Ground motion	Sa (T1,5%) at collapse	Frame 1	
		MID (%)	MRID (%)
Imperial	(0.341 g)	2.97 (2nd storey)	0.67 (2nd floor)
Northridge	(0.489 g)	3.17 (3rd storey)	0.41 (1st floor)
Loma	(0.619 g)	5.02 (7th storey)	0.56 (8th storey)
San Fernando	(0.476 g)	3.48 (6th storey)	1.21 (4th storey)
Tabas	(0.445 g)	2.75 (3rd storey)	0.29 (2nd storey)