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Mechanical response of tensegrity dissipative devices incorporating shape memory alloys

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Abstract. To optimize the seismic performance prescribed by modern structural codes, buildings and infrastructures must provide adequate safety for design level earthquake excitations, with limited levels of damage. This paper deals with the computational modelling of a bracing system with tensegrity architecture, which operates as a lightweight mechanical amplifier of longitudinal displacements in the transverse direction, efficiently limiting the inter-story drifts while dissipating energy. The proposed brace is based on a D-bar tensegrity structure with a rhomboidal shape comprising Shape-Memory Alloy (SMA) tendons. The SMA tendons can develop austenitic-martensitic (solid to solid) transformations, which enable them to amplify the signals into wide super elastic hysteresis, while subjected to mechanical cycles, comprising strains up to 6÷8%, with no residual deformations. The enhanced energy dissipation of the proposed SMA-D-bar (SMAD) braces are demonstrated through computational simulations of the response of braced frame to real earthquake events. The efficiency of the intended bracing to minimize the seismic impact of the served structure lays the foundation for the development of novel seismic energy dissipation systems integrating principles of tensegrity with superelasticity.

1. Introduction

Increasing attention are receiving mechanical metamaterials with unique dynamic properties not found in traditional materials [1]-[3]. Seismic metamaterials are unique; they either shield building including structures from seismic waves [4] or make use of novel seismic isolators based on lattice metamaterials, whose properties are mainly derived from their internal architecture, more than the nature of the component materials [5]-[6]. Metamaterials with nonlinear response can dynamically adjust their properties to the amplitude of traveling waves [7]. The category of nonlinear metamaterials featuring an internal tensegrity structure is especially significant since the response of such systems can be easily controlled by tuning internal and external prestress variables [8]. Dissipative bracing mechanisms provide effective resources in structures prone to extreme vibrations by passively dissipating the energy [9]. Such structures operate as nonlinear mechanisms and interact with the served structure, being capable of dissipating energy through, e.g., plastic response. In recent years, the use of displacement amplification dampers and superelastic Shape Memory Alloy (SMA) components within bracing systems has been extensively studied to account for re-centering capabilities [10]. The current research work deals with the use of an anti-seismic bracing device based on a tensegrity structure configured with SMA cables. The analyzed brace comprises a D-bar system, i.e., a planar tensegrity structure



consisting of four bars shaped like a rhombus, which is balanced internally by inserting two perpendicular SMA cables (or strings).

Because of its geometric non-linearities, the SMAD brace examined here will significantly intensify the longitudinal displacement applied in the transverse direction, causing the transverse SMA cable to undergo a pronounced axial strain. Thus the structure can dissipate a large quantity of energy through its superelastic responses, without suffering significant deformations [11]. The SMAD brace's remarkable displacement amplification property is magnified when the device achieves a compact and tapered shape, which is especially convenient for designing non-invasive bracing systems. The geometry correlates with that of the scissor-jack damper described in ref.[12], with the difference that the SMAD brace replaces the viscous damper with SMA strings. It can be used profitably to shape novel seismic meta-materials inspired by tensegrity concepts [13]. After the installation of SMAD braces in benchmark building, a fragility analysis has been performed to illustrate their peculiar ability as anti-seismic protection gear.

2. Methodology

This study is focused on the development of a seismic bracing system with tensegrity architecture, which serves as a passive energy dissipation (PED) device, on combining noticeable displacement amplification properties with the superelastic response of SMA tendons. Various designs (as stated in Ref. [12]) were studied before adopting the scissor-Jack design by replacing the viscous damper with the SMA wires. A distinctive strategy has been incorporated in this structure and a system with D-Bars has been formed, as shown in Figure 1 (a), which shows the Scissor-Jack damper device equipped with SMA tendons. This design allows us to operate in a way that enables the element to be stretched while trying to move vertically.

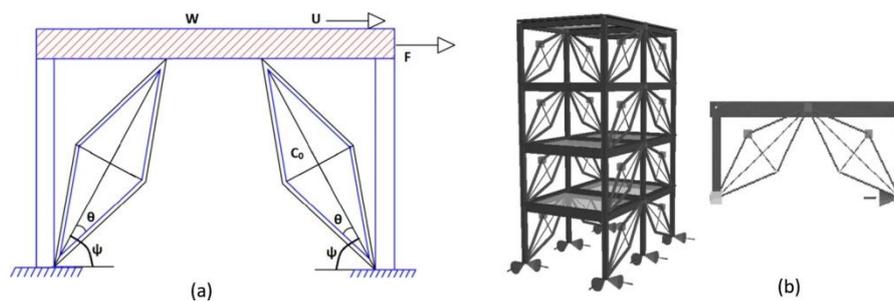


Figure 1. (a) Scissor-Jack Damper with SMAD brace, (b) Building model reinforced with C4T2 bracing devices.

Finally, the designed tensegrity-based device was installed on the benchmark structure and analyzed for its efficiency through fragility analysis, which is discussed in next section.

3. Numerical results

To computationally test the effects of the internal geometry on the mechanical response of the proposed unit, a small scale functional model of a SMAD brace was developed, which is hereafter referred to as C4T2 bracing (see Figure 1(b)). Both of the compressive struts consisted of two parallel 440 mm long pine wood bars with 35 upper 5 mm 2 cross-sections, joined at the mid-length of the bars between them. Hinges were mounted at the extremities to allow free rotation. NiTi superelastic strings (SMA wires) ($d = 0.406$ mm) were used to build the device tendons with a composition of 54.5-57 wt.-% Ni.

3.1 General description of the building

The research would concentrate on a 3-D model of the house (a four-story(4-story) steel building (Fig.1(b))), with a plan of 10.0 m by 6.0 m and altitude of 15.275 m. Throughout the x-direction, the bays are 5.0 m long, with a set of twice bays, and one separate bay in the y-direction. The building's

lateral load-resistant mechanism consists of steel MRFs, with square tube sections and composite beams with broad girders on the flanges. Standard heights of floor to floor are 3.50 m. The bases of the columns are configured as fixed to the surface (at ground level). The floors are built of a composite structure consisting of wide-flange steel beams that work compositely with the floor slab, except for of the roof slab that is materialized by a reinforced concrete slab with a flat steel deck at its base. The floor structure includes diaphragm operation, and the horizontal plane is presumed to be rigid. It is presumed that the inertial effects of each point are conveyed uniformly to each perimeter of MRF by the floor diaphragm.

3.2 Ground motions for the structural analysis

To evaluate the seismic vulnerabilities and the damages caused by seismic actions, multiple strong ground movement scenarios were considered using the RSSIM program [15] relying on the non-stationary stochastic method [16] which takes into consideration the effects of finite faults. Using the earthquakes produced and incorporating different ground movements in two perpendicular directions, forty instances of seismic loading were created, ranging from 20.57o 94.64 s.

3.3 Seismic vulnerability assessment

The seismic vulnerability of the 4-story structure was assessed using a probabilistic method. Using a statistical approach [17], this method allows to consider the variability of the seismic activity and of multiple main FE model variables. In Table 1, the selected variables are considered to have normal distribution and are characterized.

Table 1. Probabilistic characterization of key parameters.

Variable	Units	Mean	St. Deviation
f_y (columns)	MPa	380.000	26.500
f_u (columns)	MPa	425.361	17.014
ε_u (columns)	%	23.421	1.405
f_y (beams)	MPa	300.000	21.000
f_u (beams)	MPa	438.841	17.554
ε_u (beams)	%	24.954	1.497
E	GPa	200	0.600
ν		0.300	0.009
γ (concrete)	kNm ³	24.000	0.960

Successive incremental dynamic analyzes (IDAs) allow the identification of multiple damage states and the creation of fragility curves that can be used to estimate the probability of damage and the associated level of failure for provided peak ground accelerations (PGAs). To implement an IDA, a sequence of ground motion time-histories of increasing intensity are imposed on a nonlinear numerical model of the structure. In the present scenario, the PGA has been incrementally scaled (10 steps) from a low elastic response value, 0.1 g, up to 1.0 g, which ensures the failure in more than 50% of the FE model. To describe the damage levels, 80 IDA envelope curves were created by performing 640 nonlinear analyzes.

The assessment of the structural damage was performed using five damage state (DS) thresholds [18]-[19], which are DS0 = none, DS1 (slight) = 0.7 dy, DS2 (moderate) = dy, DS3 (extensive) = DS2 + 0.25 (du - dy), DS4 (collapse) = du. The description of the DS thresholds was made according to [20], using the generalized bilinear form of the curves of the IDA envelope.

The DS thresholds for an IDA envelope curve, together with its bilinearization are shown in given in Figure 2.

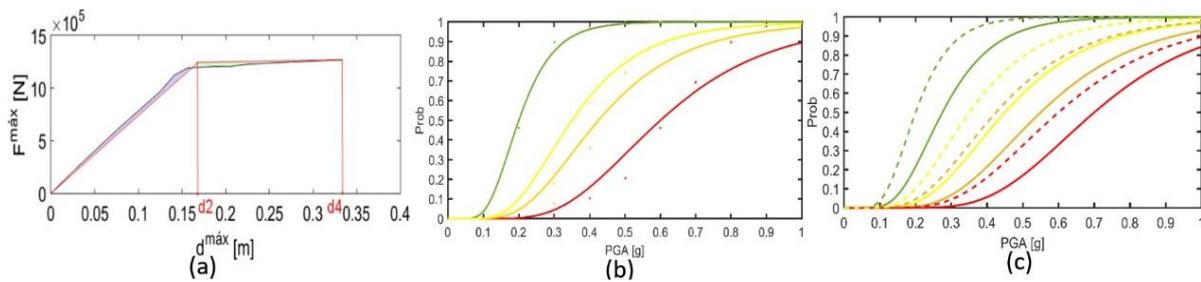


Figure 2. (a) Damage states thresholds for an envelope IDA envelope curve (b) Fragility curves of unbraced structure, (c) Fragility curves of braced structure

For DS threshold the associated fragility curve is defined as a function of the IDA displacement by the 50% probability of exceeding the respective threshold. Each fragility curve is defined by Equation 1, assuming it follows a standard log-normal cumulative distribution function ϕ .

$$P[DS_i/d] = \phi \left[\frac{1}{\beta_{DS_i}} \ln \left(\frac{d}{DS_i} \right) \right] \quad (1)$$

Where d is the displacement of the IDA and β_{DS_i} is the standard deviation of the natural logarithm of DS_i variable. The resulting global curves of fragility, for both the unbraced and C4T2 braced structures are given in Figures 2 (b) and 2 (c), respectively. To assess the seismic vulnerability of the structure, the probability of exceeding the DS thresholds for PGAs of 0.3 g (moderate earthquake ground motion) (Figure 3) and 0.65 g (strong earthquake ground motion) were computed. One can easily verify that the presence of proposed bracings in the structure decreases its seismic vulnerability.

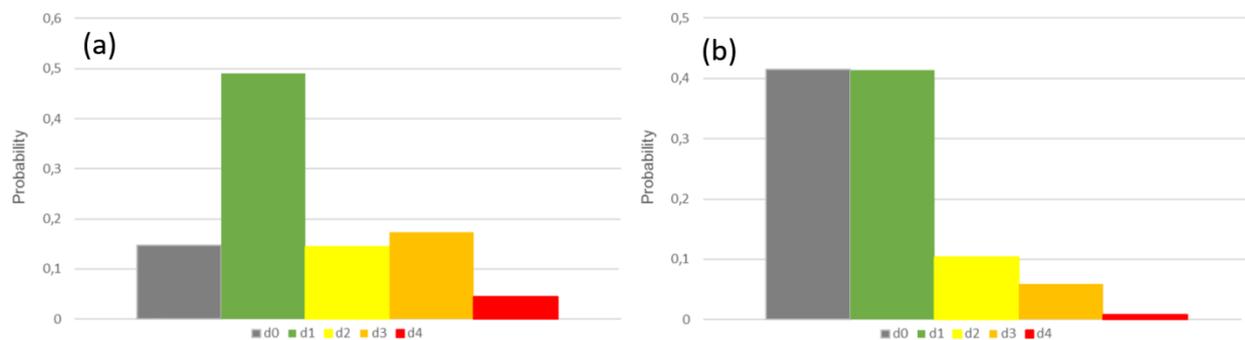


Figure 3. Probability of exceeding the DS thresholds for a PGA of 0.3g (a) unbraced structure (b) braced structures

4. Concluding remarks

The present paper has studied the seismic response of a tensegrity-based bracing with super elastic tendons. The given numerical simulations on a benchmark building model have shown that tensegrity inspired bracings can excel in structural seismic control. From the performed analysis one can indeed draw the following conclusions:

- i. The compression efficiency of the proposed C4T2 bracing is associated with a geometrical advantage, combined with the use of tensile members that have been shown to exhibit large load to mass ratios.
- ii. The proposed C4T2 tensegrity bracing acts as a mechanical amplifier for longitudinal displacements, increasing the level of deformations experienced by the transverse SMA tendons, and, hence, potentiating damping.

- iii. In spite of its limitations, the proposed numerical model is able to reasonably apprehend the main features of the force-displacement diagrams shown by the proposed bracing.
- iv. Based on the seismic vulnerability assessment it is possible to conclude that the proposed C4T2 bracings successfully mitigate the earthquake-induced damages, reducing the probability of collapse and that the proposed control approach shows great potential for seismic mitigation in civil engineering applications.

We address the experimental verification of the numerical results presented in this study to future work.

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