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COMPUTATIONAL MODELING OF THE SEISMIC RESPONSE OF TENSEGRITY DISSIPATIVE DEVICES INCORPORATING SHAPE MEMORY ALLOYS

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Abstract. Infrastructures and buildings must have sufficient protection for design level earthquake excitations while minimizing major damage to comply with existing seismic design criteria. This paper explores the computational modeling of a tensegrity based brace, which helps dissipate energy while preventing inter-story drifts. The proposed brace integrates a D-bar tensegrity structure, shaped like a rhombus, with Shape-Memory Alloy (SMA) cables or tendons. These tendons grow austenitic-martensitic-austenetic (solid to solid) transformations, which make them more susceptible to mechanical stress when taking strain, and amplifying the stress into broad superelastic hysteresis, even after repeated mechanical cycles that require strains of up to $6\% - 8\%$. In addition in this article two special classes of the tensegrities are discussed namely 2D and 3D braces. 3D braces have been proven more efficient because of an enhaced capacity of energy dissipation, and also due to their improved safety against buckling. The effectiveness of the planned bracing paves the way to the development of innovative systems of seismic energy dissipation that combine tensegrity concepts with superelasticity.

1 INTRODUCTION

Mechanical metamaterials containing special dynamic characteristics are becoming more well-known as attention increases [2, 3]. The primary feature of seismic metamaterials is that they serve either to protect structures and buildings from earthquake excitations such as seismic waves [4], or to use innovative isolators, the properties of which are primarily derived from their design and architecture, instead of the components used [5, 6]. The metamaterials can dynamically change their properties if they have nonlinear response [7]. Internal and external prestress variables regulate the response of these systems very well[8]. Dissipative bracing mechanisms support structures that are subject to high levels of vibration by dissipating the resulting energy[9]. The designed structures acts as mechanisms with non-linear behaviour and interact with the structure, for example, able to transfer energy through, e.g., flexible plastic response. Recently, re-centering abilities have been thoroughly studied in order to meet up with displacement dampers with high amplification & superelastic parts such as SMA cables inside bracing systems[10]. Recent research in this area focuses on the application of an anti-seismic bracing system using a SMA cable-based tensegrity structure. It is a D-bar device, which is a tensegrity structure made up of four bars that are formed as a rhombus, that is maintained by deploying two perpendicular cables or strings made of SMA. Due to the non-linearities of geometric configuration, the SMAD bracing system featured here will significantly raise the transverse longitudinal displacement, which will contribute to an intense axial strain in the transverse SMA cable. Thus, the system is capable of dissipating a considerable energy through outstanding superelasticity without having to undergo major deformations. In addition, an extension to this work has been provided in this work by enhancing the stability and the dissipating out of plane forces through a 3D brace. 3D brace has been designed and computation modelling has been carried out to explore the energy dissipation capacities and stability. The SMAD brace's amplifying function is intensified when the device acquires a lightweight, tapered shape that is especially useful in developing non-invasive bracing systems. [11]. The geometry closely matches with the scissor-jack damper mentioned in reference [12]. The major difference being that instead of a viscous damper, a SMAD brace is used and this reference only includes 2D dampers. This material can be used to develop innovative matamaterials with anti-seismic properties that are influenced by tensegrity concepts/designs [13]. The 3D tensegrity bar which has been studied in this article has been proven to be the best in terms of the efficiency and the also prevent the instability which might occuer in the 2D bracing system. Also the amplification factor can be enhanced to certain extent because of the dissipation of energy resulted because of out of plave forces. Following section will inlcuded the computational modelling and the amplifaction features of the systems accpompnied by the conclusions in the end.

2 METHODOLOGY

This research focuses on the design and development of a an innovative seismic brace with a tensegrity structure that functions as a unique passive energy dissipation device (PED) to combine the visible displacement amplification characteristics with the superelasticity of the SMA cables/tendons [5]. It was constructed to serve as PED device as stated in the previous section, and SMA tendons were used as part of the restitution phase. The two major classes of energy dissipation in buildings are elastic dissipation and inelastic dissipation. Elastic dissipation methods, such as PED devices, have been used in the production of this system. There are various other design which have been followed including Diagonal, the Upper toggle, Chevron, the Reverse toggle, and the Scissor-Jack have all been tested, and the Scissor-Jack design was finally adopted for installation of the 2D tensegrity unit because of better amolification factor [12]. In addition an extention to this work has been providing by developing an innovative 3D tensegrity unit as discussed in section 4.

3 2-Dimension tensegrity bar

3.1 Mechanical modeling of SMAD braces

In this section 2D tensegrity unit has been discussed along with the computational modelling carried out on the same unit.

Considering the SMAD device shown in Fig.1, which represents the reference structure under null external force (solide lines) as well as its deformed configuration under the influence of vertical force P on the upper vertex (dashed lines). We suppose a vertical roller restricts the top vértex, while a fixed hing restricts the lower vertex. The subsequent sections demonstrate the mechanical model utilized for the SMAD brace and the related SMA wires.

Mainly due to the SMAD brace symmetry and to the loading condition studied, it's clear to notice that the similar axial force is present on all bars of a framework, N, which is assumed as positive compressive force. Instead, the longitudinal string has a vertical force Y, while the horizontal tensile force X is applied on a transverse string.

By resolving the equilibrium equation in the deformed configuration of the top and the side nodes, the following terms are assigned to the members' forces in equilibrium conditions.

$$N = X/\cos\hat{\theta}, \quad P = 2N\sin\hat{\theta} - Y = X\tan\hat{\theta} - Y \tag{1}$$

Here $\hat{\theta}$ referes to teh angle made by bars and the string (horizontal) in deformed condition. (Same case of θ has been considered in reference configuration, cf. Fig. 1).

The buckling behavior of the SMAD brace is significant in relation to a beam that is composed of the identical materials and has a length of $2h$. Designing structures such that they produce the same buckling load yields a simple method for showing that the SMAD brace's mass, m_1, is proportional to the straight beam's mass, m_0, according to the preceding equation (refer to [8]).

$$m_1/m_0 = (2\sin^5\theta)^{-\frac{1}{2}} \tag{2}$$

When $\theta > 60.5$ degrees, this equation yields a m_1/m_0 ratio smaller than one while it returns a $m1/m0$ ratio of 0.73 when $\theta = 80$ degrees. In conclusion, it can be seen that a brace of increased density and taper ($\theta \gg 60.5$ degrees) exhibits greater buckling load, as opposed to a comparable straight beam of equivalent mass.

Assume that, under some arbitrary alteration of the structure, the bars are acting as rigid bodies, which results in following equation

$$\left(h - \frac{v}{2}\right)^2 + \left(l + \frac{u}{2}\right)^2 = b^2 = \text{const} \tag{3}$$

here, b characterizes the bar length, and v and u and parameters represent the transverse and longitudinal displacements of the structure respectively (cf. Fig. 1). The axial stiffness of the bars is more than that

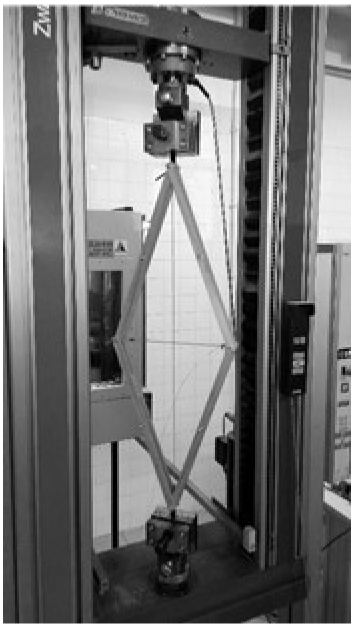

Figure 1: Illustration of a SMAD brace under testing (reproduced with permission from [6].

of the strings when it comes to tensegrity structures (see, e.g., [8]). Transverse displacement, u, can be proportional to longitudinal displacement, v, as seen in Eqn (3). It is convenient to recognize that the following feasible solution to Eqn. (3) results from parameterizing the displacement v by the bar length b resulting in $v = \beta\, b$.

$$u/v = \left(\sqrt{4\cos^2(\theta) - \beta(\beta - 4\sin(\theta))} - 2\cos(\theta)\right)/\beta \tag{4}$$

According to Eqn. (4), u/v is $\tan\theta$ in the limiting case with $\beta \to 0$, corresponding to considering insignificantly small deformations from the source configuration.

From this equation , it can be concluded that as θ approaches to 90 degree, the u/v ration tends to infinity and providing high amlification factor.

4 3-Dimensional tensegrity bar

A novel approach, as discussed before has been used to develeop a 3D model of the 3D tensegrity brace to overcome the issues which are present in the 2D version of the system. This system is more efficient in terms of the stability, dissipating more energy because of the design. Fig. 2 shows 3D models of the T-Bar unit. Fig. 2 contains three bars of the lv form. With any number of bars of the l_v form, one can construct three-dimensional T-Bar units. N = 3 is by far the most effective for a triangular cross-section. For such envelope constraints, the N = 4 unit can be more beneficial s it has a square cross-section. Analysis carried out as described above would result in self-similar three-dimensional realizations of ideal compressive structures. The calculation is the identical like in the planar method, apart from the fact that in includes N time strings and three time bars l_{vi}.

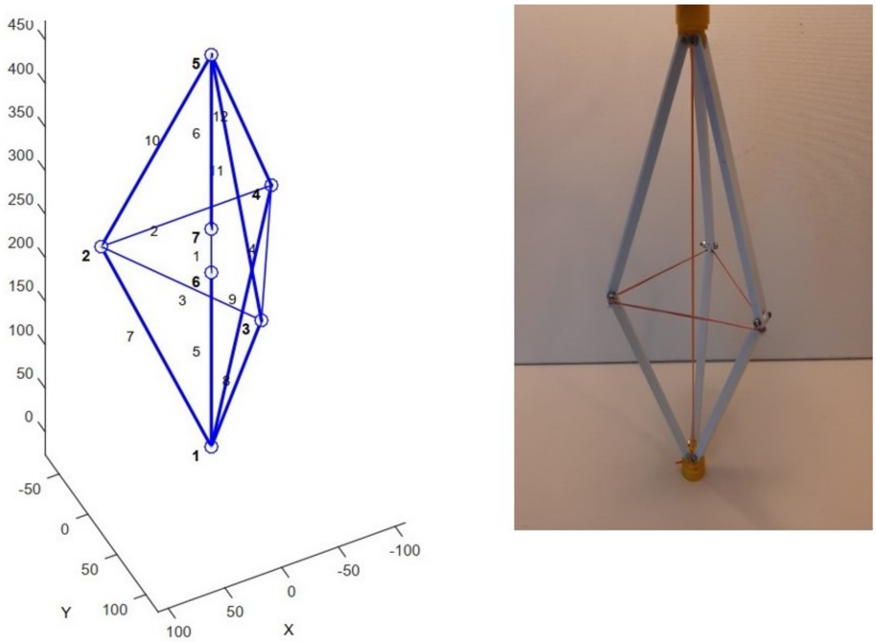

Figure 2: 3-dimensional SMAD brace model (left) and physical prototype (right).

$$u_n = m_n/m(l_0) = \frac{1}{2^n} + \sum_{i=1}^{n} \frac{tan^{5/2}\alpha_i}{2^i} + \sum_{i=1}^{n} \varepsilon(1+tan^2\alpha_i) \tag{5}$$

Hence,Eqn (5) demonstrates a mass for the three-dimensional bar of the compressive l_v-type N bar following n iterations, results in

$$u_n^N = \frac{1}{2^n} + \frac{N}{2} + \sum_{i=1}^{n} \frac{tan^{5/2}\alpha_i}{2^i} + \frac{N}{2}\sum_{i=1}^{n} \varepsilon(1+tan^2\alpha_i) \tag{6}$$

The optimum number of iterations, n * for 3-dimensional T-Bar structures, with constant or with constant diameter w, can be calculated by following the same steps as in eqn (5) in the previous section. The above equation reduces to eqn (7) for the three-dimensional case with N = 3 and constant α.

$$u_n^3(\alpha_i = \alpha) = 2^{-n} + (3/2)tan^{5/2}\alpha(1-2^{-n}) + (3/2)n\varepsilon(1+tan^2\alpha) \tag{7}$$

This 3D tensegrity system is an extension to the previous works done the authors. In 3D system N=3, where N is the number of the bars. The value of N can very from N=2 to N=3,4,5 etc. In the case of the N=3, it becomes the trinangular case whereas if N= 4 it becomes the square cross-section, which can be preferable in some situtations but the case with N=3 has been proven to be the best in terms of effiency and stability.

5 CONCLUSION

In the paper, an effort has been made to study the seismic response of the various tensegrity systems including 2D and 3D units. As discussed above it has been seen that 2D and 3D system both works on the same principle of the self similar rule. Self-similar concept is represented by a repeated process when another geometrical object is substituted. Fractals are generated as self-similar iterations get larger and larger. In 2D system N=2, and in 3D system N=3, where N is the number of the bars. The value of N can very from N=2 to N=3,4,5 etc. In the case of the N=3 it becomes the trinangular case whereas if N= 4 it becomes the square cross-section, which can be preferable in some situtations but the case with N=3 has been proven to be the best in terms of effiency and stability. Further when the strings are made of SMA cables, then the structure turns in to a passive energy dissipation device which is also a core focus of the research. The key advantages of the SMAD braces compared with viscous dampers are the inclusion of SMA cables in place of widespread broader dispersion systems, the growth of buckling tolerance with structural tapering and its re-centering capability and displacement amplification properties depending on the device geometry rather than on the material's chemical nature. Future work will investigate the employement of sustainable construction materials for the fabrication of the struts of SMAD braces [14], as well as the laboratory testing of 3D braces under seismic-type loading [15].

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