Superelastic tensegrity bracing system

Tensegridade aplicada a um sistema de contraventamento com cabos superelásticos

Filipe Amarante dos Santos
Andrea Micheletti

Abstract

The present paper explores the capabilities of a superelastic pre-strained bracing acting as a seismic protection system. The proposed bracing is inspired by tensegrity concepts, showing certain geometrical advantages which yield a passive control device with an optimized structural behaviour. The bracing operates as a mechanical amplifier of longitudinal displacements, increasing the energy dissipation capabilities of its two antagonistic superelastic tendons. It is also showed that the damping capabilities of the bracing can be further enhanced by pre-straining the superelastic tendons, enabling higher martensitic transformation ratios. The forces associated with the introduction of prestress in ties are not transferred to the structure, but rather to a self-equilibrated inner compression cell, built up of four struts arranged in a four-bar linkage.

Resumo

O presente artigo explora as capacidades de um sistema de contraventamento equipado com cabos superelásticos, como elemento estrutural de proteção sísmica. O contraventamento proposto é inspirado na tensegridade, apresentando algumas vantagens geométricas que o tornam um elemento de controlo passivo com um comportamento estrutural otimizado. O contraventamento apresenta um efeito pantográfico, fazendo a amplificação mecânica dos deslocamentos longitudinais introduzidos, aumentado assim as capacidades de dissipação de energia dos seus elementos superelásticos antagonistas. É também demonstrado que as capacidades de dissipação do contraventamento podem ser potenciadas através da introdução de um pré-esforço inicial nos elementos de restituição superelásticos, permitindo atingir maiores rácios de transformação martensítica. As forças associadas à introdução do pré-esforço nos cabos não são transmitidas à estrutura, sendo absorvidas ao nível de uma célula de compressão autoequilibrada constituída por quatro barras ligadas entre si.

Keywords: Tensegrity / Superelasticity / Shape-memory alloys / Damping / / Seismic bracing / Antagonistic elements

Palavras-chave: Tensegridade / Superelasticidade / Ligas com memória de forma / / Amortecimento / Contraventamento sísmico / Elementos antagonistas

Filipe Amarante dos Santos

Assistant Professor
CERIS, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa
Caparica, Portugal
fpas@fct.unl.pt

Andrea Micheletti

Researcher
Dipartimento di Ingegneria Civile e Ingegneria Informatica (DICII)
Rome, Italy

SANTOS, F. [*et al.*] – Superelastic tensegrity bracing system. **Revista Portuguesa de Engenharia de Estruturas**. Ed. LNEC. Série III. n.º 16. ISSN 2183-8488. (julho 2021) 51-58.

1 Introduction

In order to comply with the seismic performance required by modern structural codes, buildings are expected to provide adequate safety for design level earthquake intensities, with limited levels of structural and non-structural damage. Innovative seismic structural protection systems based on novel energy dissipation devices that minimize damage and substantially reduce repair costs following an earthquake are, hence, currently needed. In this paper a seismic bracing is developed and investigated, based on a tensegrity structure (TS). A TS is built of compressive struts and tension ties attached to the extremities of the struts. Properly designed TSs can be arranged in very stable and efficient geometrical configurations, that can achieve great strength with small mass, since the material is only used in the essential load paths. TSs are easy to fold, deploy and adjust, offering many operational and portability advantages [1]. As they are not subjected to bending or torsion, they can be more accurately modelled and since their mechanical behaviour originates from their geometry, they are applicable from small to large scales, with physical limitations depending on the materials employed [2, 3].

NiTi superelastic shape-memory alloy tendons are used to provide the proposed tensegrity bracing with increased damping capabilities. NiTi alloys can develop martensitic transformations, which are solid state crystallographic transformations between a high energy phase, austenite, and a low energy phase, martensite. Such transformations are triggered by changes either in temperature or stress and enable SMAs to develop a wide hysteresis, while subjected to mechanical cycles comprising strains up to 6%, with no residual deformations. This superelastic hysteresis translates into the ability of SMAs to dissipate energy and has made them particularly suited for kernel elements in seismic mitigation bracing systems [4, 5, 6].

2 Description of the proposed bracing system

2.1 A tensegrity inspired bracing

In the traditional definition of tensegrity structures the compressive members are disconnected, only one strut converges in each node, yielding what is usually called Class-1 tensegrity elements. When there are at most N struts connected at a node we speak of Class-N tensegrity structures [1]. To design an efficient bracing system that can carry compressive loads with small mass, Class-2 tensegrity modules were explored, like the one shown in Figure 1. The basic principle responsible for the compression efficiency of this bracing system is associated with its geometrical advantage.

By designing the C4T2 bracing, comprising four compressive struts and two tendons, to buckle at the same load P as the column represented in Figure 1(a), of mass m_1, assuming a slack vertical tendon ($T_v = 0$), it can be shown that the total mass m_1 of the C4T2 system is given by $m_0 = m_1\,(2 \sin \theta)^{-1/2}$ [1]. The mass ratio m_0/m_1 is plotted in Figure 2, as a function of the angle θ.

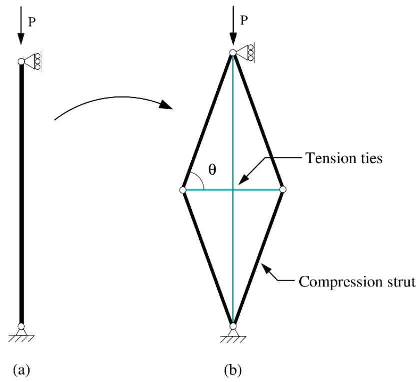

Figure 1: C4T2 bracing tensegrity element

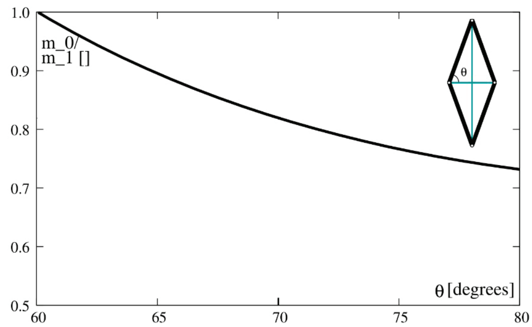

Figure 2: Mass ratio as a function of the angle q.

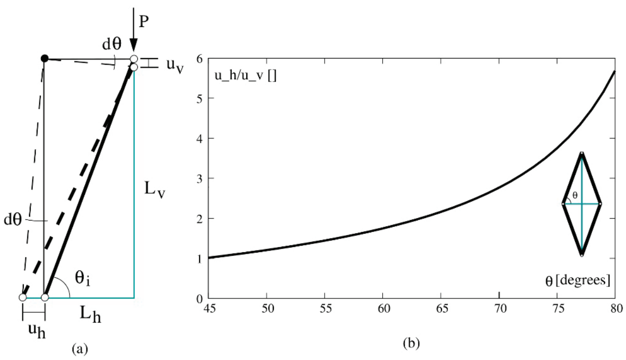

Figure 3: Geometric amplification factor of the C4T2 bracing tensegrity element

One can see that for angles greater than 60 degrees m_1 is less than m_0, with a mass reduction amounting to about 26%, for $\theta = 80$ degrees. The amount of damping that can be delivered by passive bracing systems during dynamic events is related to the level of displacements experienced by the structure during such an event [7]. Generally, increased displacements lead to higher damping. However, the relative displacements between the extremities of structural bracings, even during seismic events, can be rather low. This hinders the performance of SMA based bracings, which rely on high deformations to dissipate energy. One interesting feature of the proposed C4T2 tensegrity bracing is that it acts as a mechanical amplifier for longitudinal displacements, increasing the level of deformation experienced by the transverse SMA tendon, and, hence, promoting damping. This amplification is illustrated in Figure 3(a), where the longitudinal displacement u_v, associated with load P, is transformed in a higher transverse displacement u_h. The geometric amplification factor, in a small deformation regime, is equal to the ratio between the length of the longitudinal and transverse tendons. This amplification factor is plotted in Figure 3(b) as function of the angle θ. One can see that for θ between 45 and 80 degrees the amplification factor can amount up to almost 6.

2.2 Superelasticity for vibration control

It has been already shown in the literature [8, 9, 10] that the performance of superelastic based passive damping devices can be considerably improved by the use of antagonistic pairs of pre-strained superelastic elements. The C4T2 bracing takes advantage of this feature since it comprises two tension ties working in phase-opposition; see Figure 4(a). However, as the length of these ties is not equal, the response of the bracing in tension and compression differs. In order to obtain an equal response of the bracing for both tension and compression, the configuration of the C4T2 bracing was changed into a C8T2 configuration, like the one depicted in Figure 4(b). This new configuration has four additional compression struts, that form an interior C4T2 tensegrity unit, with equal length tension ties. This way one obtains a superelastic bracing device with a stable cyclic behaviour, also comprising displacement amplification features.

Diagonal cable bracings only work in tension. As cables become slack, they yield no additional stiffness to the system. Usually frame bracings rely on two complementary diagonal members, arranged in a X configuration, to guarantee that at least one of the cables is always tensioned. It is not advisable to apply a significant amount of pre-strain in theses cable bracings, since the forces associated with this pre-strain must be equilibrated by the structure. As the proposed C8T2 bracing system comprises a self-equilibrated tensegrity unit its superelastic ties may be pre-strained without transferring any additional force to the structure; see Figure 4(c).

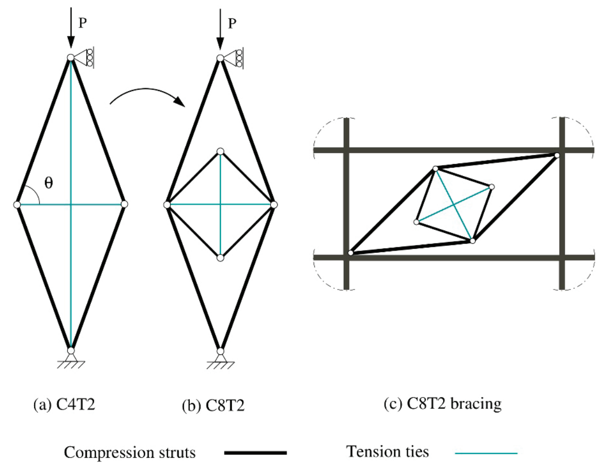

Figure 4: C8T2 bracing tensegrity element

As the superelastic ties are arranged in an antagonistic manner we also obtain a reversible-actuation system, inspired by muscles that work in pairs. An antagonistic actuation requires the assembly of two opposing SMA active elements in which the contraction (upon heating) of one pre-stressed actuator causes the opposing actuator to stretch, arming it to a subsequent heating, as described in [11]. One of the main advantages of these antagonistic systems is the fact that they do not need continuous power, but just an electric pulse, to switch permanently to a new configuration. This feature is used in the C8T2 bracing to promote the repositioning of the system.

3 Benchmark example of a C8T2 bracing tensegrity element

A methodology for the design of antagonistic tensegrity-SMA structures has been developed by the authors, describing the evolution of superelastic tensegrities, subjected to load and temperature changes, by a system of ordinary differential equations written in matrix form, solved by standard numerical routines. The analytical formulation and computational procedure of this method is thoroughly described in [11]. In this section, a benchmark example of a C8T2 bracing tensegrity element subjected to a prescribed cyclic loading is analysed, using our procedure for the design and simulation of simple tensegrity modules equipped with antagonistically connected superelastic SMA cables.

3.1 Geometry and loading definition

Taking advantage of the mechanical amplification features of the C8T2 bracing it is possible to tailor its configuration in order to explore the full length of the martensitic transformation in its superelastic restraining elements. A 4.0 m wide by 3.0 m tall structural frame is used to perform the numerical tests on the C8T2 tensegrity element, yielding a bracing with a total length of 5000 mm ($L_{bracing} = 2\ L_v$). By basic trigonometric and arithmetic operations, it can be shown that it is possible to obtain the length of the superelastic cables ($L_{SMA} = 2\ L_h$), nested in the inner cell of the C8T2 unit, as a function of the total length of the bracing ($L_{bracing}$), the imposed longitudinal displacement (ΔL) and of the desired design strain. L_{SMA} can be hence computed according to $L_{SMA} = (\Delta L.\ L_{bracing} / \varepsilon_{obj})^{1/2}$. By using the HAZUS definition of average inter-story drift (ISD) ratio of structural damage states [12] we can set a maximum threshold for ΔL so as to obtain a slight damage state (0.6%) for a structure associated with low-rise buildings and a Moderate-Code design level. For an ISD of 0.6%, ΔL yields 14.4 mm. In order to prevent slackening of the superelastic cables during mechanical cycling and foster the full development of the martensitic transformation, we introduce an initial pre-strain in the cables of 3.2%. This means that we have an additional 3% strain up to the full completeness of the martensitic transformation in the cables, which amounts to about 6%. From then on, we will be elastically loading detwinned martensite. With these input parameters, we obtain $L_{SMA} = 1550$ mm. The superelastic restraining elements were assumed to be built up of 10 small cables of 1 mm diameter each. The remaining variables that allow for the full material characterization of the superelastic elements, which were used during the numeric simulations, are listed next:

M_f = – 45 °C (martensite finishing temperature at zero stress)
M_s = – 35 ° (martensite starting temperature at zero stress)
A_s = –15 °C (austenite starting temperature at zero stress)
A_f = – 5 °C (austenite finishing temperature at zero stress)
E_M = 20000 MPa (martensite Young's modulus)
E_A = 35000 MPa (austenite Young's modulus)
C_M = C_A = 6.5 MPa°C^{-1} (Clausius-Clapeyron coefficients)
Θ = 0 MPa°C^{-1} (thermoplastic coefficient)
ε_L = 0.04 (recoverable strain)

Isothermal conditions were assumed during the tests, for simplicity sake. In Figure 5 we shown the geometry of the obtained C8T2 bracing.

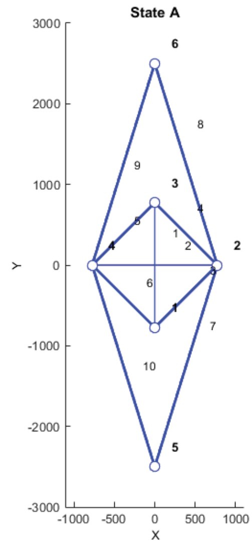

Figure 5: Geometry of the C8T2 bracing

The bracing was subjected to a mechanical cycle comprising a force with a maximum value of 9000 N, and a subsequent temperature cycle in Cable 1 to reposition the system to its original configuration, according to the scheme shown in Figure 6.

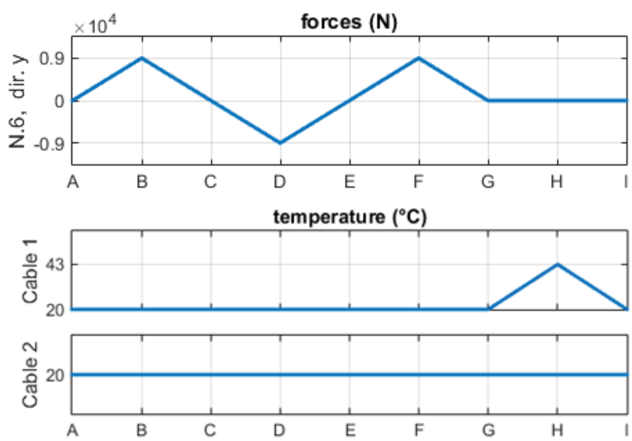

Figure 6: Loading cycle

3.2 Results of the numerical tests

In Figures 7 and 8 we show the stress-strain and stress-temperature diagrams associated with state A, respectively, which corresponds to the introduction of an initial pre-strain in both cables, amounting to 3.2%. An ambient temperature of 20ºC is considered for all the numerical tests.

In Figures 9 through 14 are shown the stress-strain diagrams corresponding to states B through G, respectively, for both cables. These states are associated with the mechanical loading of the bracing.

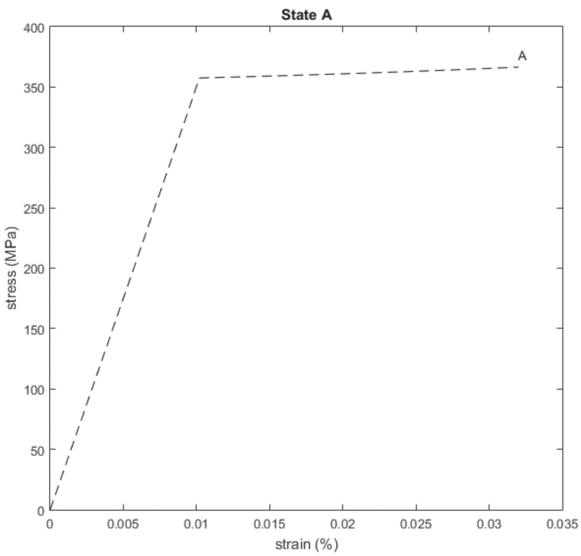

Figure 7: Stress - strain diagram for state A (initial pre-strain)

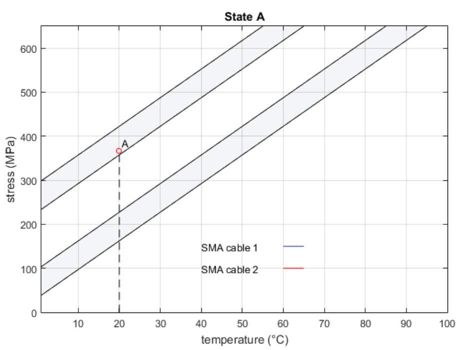

Figure 8: Stress - temperature diagram for state A

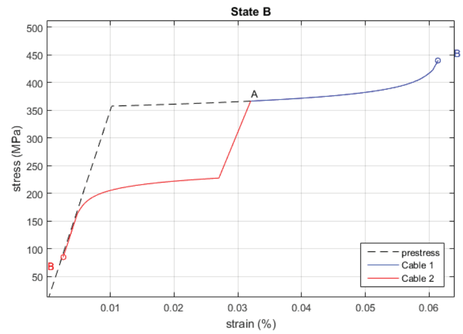

Figure 9: Stress - strain diagram for state B

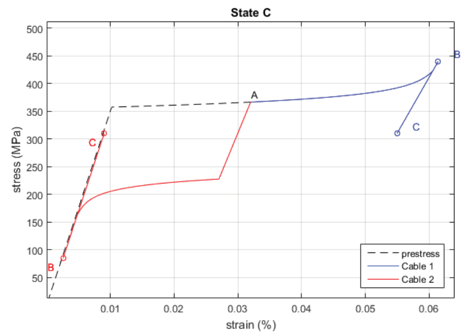

Figure 10: Stress - strain diagram for state C

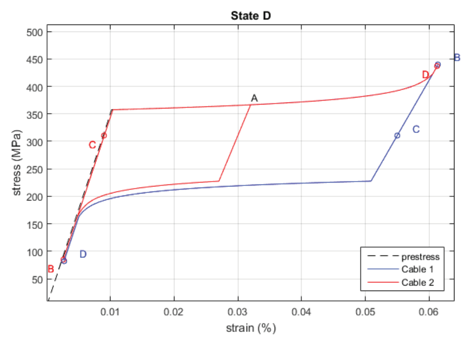

Figure 11: Stress - strain diagram for state D

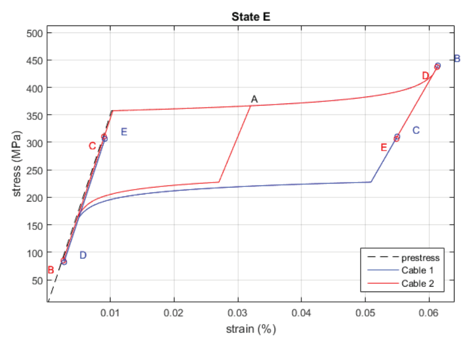

Figure 12: Stress - strain diagram for state E

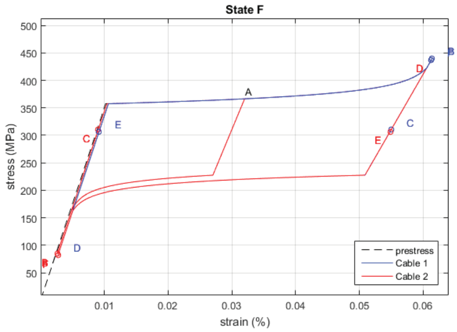

Figure 13: Stress - strain diagram for state F

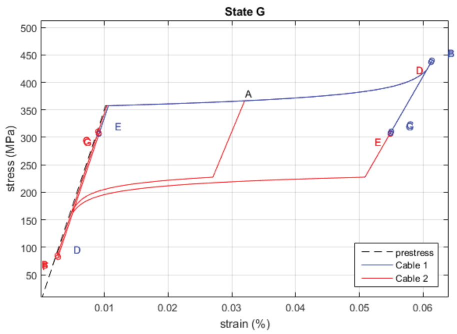

Figure 14: Stress - strain diagram for state G

In Figures 15 through 18 are presented the stress – strain and stress – temperature diagrams for both cables, associated with states H and I. These states are associated with the temperature cycle of the bracing.

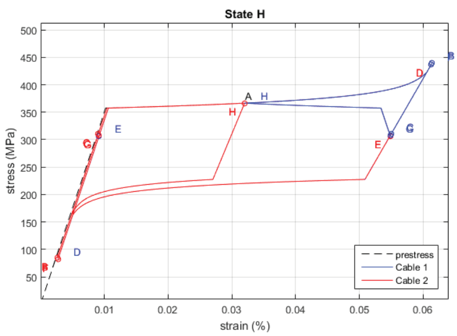

Figure 15: Stress - strain diagram for state H (heating)

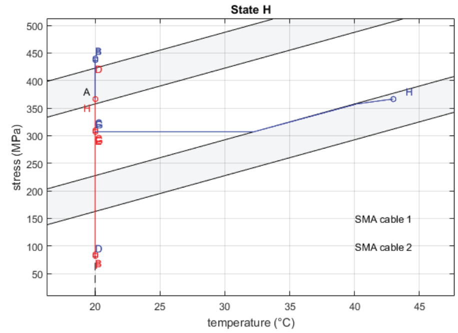

Figure 16: Stress - temperature diagram for state H (heating)

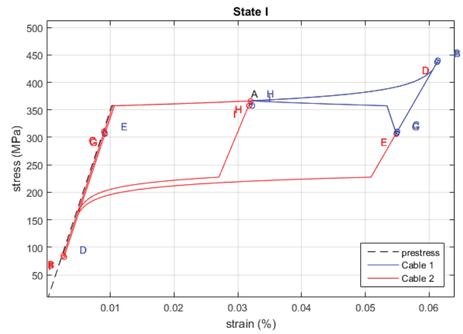

Figure 17: Stress - strain diagram for state I (cooling)

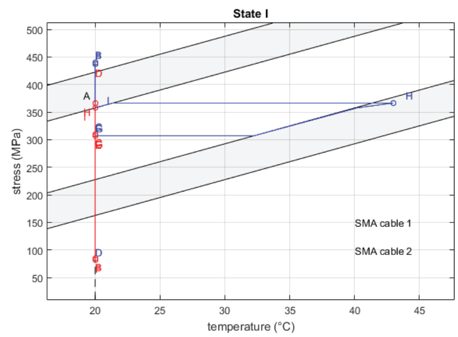

Figure 18: Stress - temperature diagram for state I (cooling)

In Figure 19 we show the overall response of the superelastic cables in terms of stress – strain and stress – temperature.

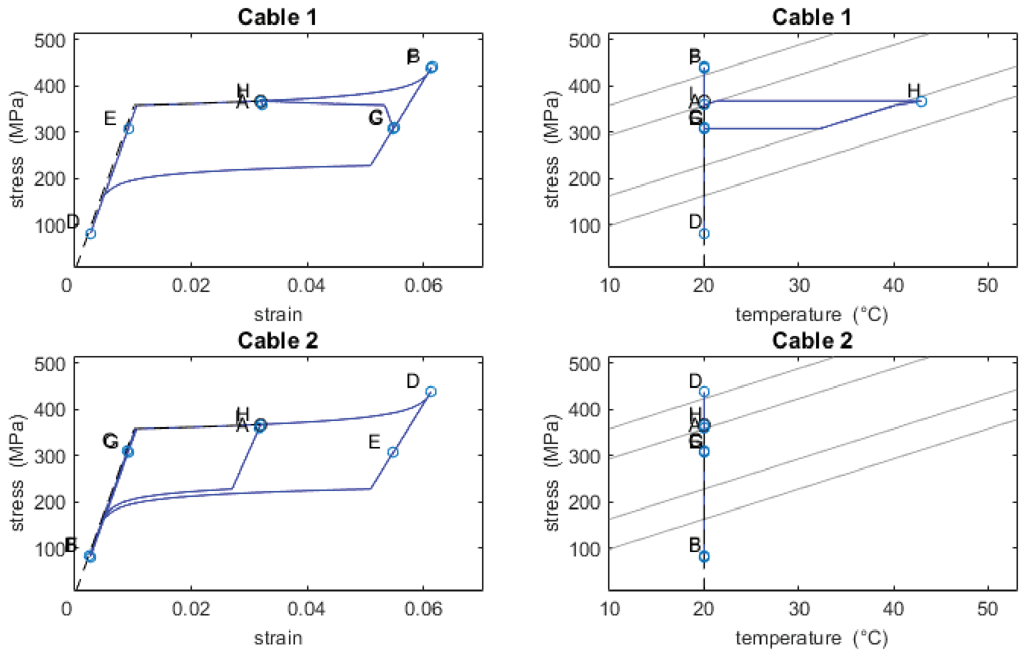

Figure 19: Stress - strain - temperature diagrams

In Figure 20 we show the resulting force-displacement of the C8T2 unit subjected to the prescribed cyclic loading.

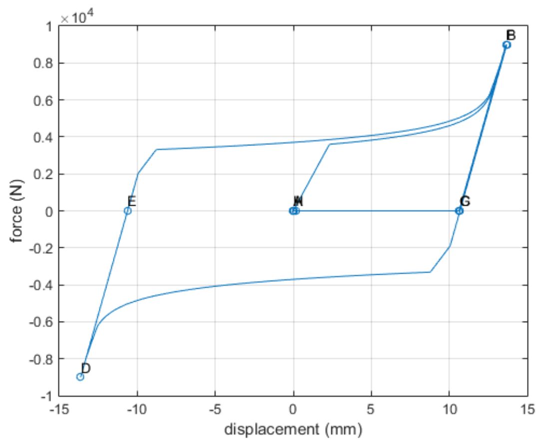

Figure 20: Force - displacement diagram

3.3 Discussion

During the numerical testing of the C8T2 bracing unit, with the two superelastic cables working in phase opposition, we show that, even for the small ISD introduced in the structure (0.6%), both cables are able to develop the characteristic flag shaped stress-strain diagrams associated with the superelastic behaviour. By introducing a pre-strain in the superelastic cables it is possible to obtain a wide shaped hysteresis, like the one shown in Figure 15, which yields a significant amount of equivalent viscous damping (25%). This damping is evaluated by the ratio of the dissipated energy during a mechanical cycle, which corresponds the area enclosed by the hysteresis, and the maximum strain energy multiplied by 4π [9]. With the introduction of pre-strain, the re-centring capabilities of the C8T2 bracing unit become less effective. However, by introducing a temperature cycle in one of the cables of the system it is possible to bring the system back to its original configuration. One also draws attention to the fact that by assuming a slight damage state for the structure its behaviour during seismic action remains mostly elastic and hence it can guarantee its repositioning by itself.

4 Conclusions

Although additional analyses would be required before on-field application of the proposed system, we believe, that the presented results highlight the effectiveness of the proposed superelastic tensegrity system. In fact, the computed equivalent viscous damping of 25%, for the C8T2 system, shows a fairly good performance with respect to its adequacy for seismic control applications. A dynamic analysis of our bracing elements falls outside the scope of the present paper, as it would constitute a major step in the research study we are carrying out, and it will be the subject of future work.

The main technical advantages of the proposed C8T2 bracing can be summarized as follows:

1) High buckling resistance due to enhanced compression efficiency;

2) High martensite transformation ratios are easily attained in the superelastic cables due to the mechanical amplification feature for longitudinal displacements, fostering higher damping capabilities;

3) Enhanced energy dissipation due to the antagonistic actuation of

the superelastic ties, also guaranteeing that at least one of the ties is always tensioned. This means that if one of the cables becomes slack, and loses its stiffness, it's guaranteed that the other tie, working in phase opposition, is conveniently tensioned;

4) The pre-straining of the ties does not introduce parasitic forces in the structure of the building. The bracing is a closed structural system (self-equilibrated) in which the pre-strain of its elements is not transferred to the structure;

5) Repositioning o the system can be fostered by the introduction of a heating-cooling cycle in one the cables of the system;

6) The system does not need to be replaced after a major seismic event due to the superelastic nature of its kernel dissipating elements. Alternative damping systems on the market are based in the yielding of their steel elements to provide for energy dissipation and, hence, need replacement after an earthquake.

5 Bibliography

[1] R. Skelton, J. Helton, R. Adhikari, J. Pinaud, W. Chan, An introduction to the mechanics of tensegrity structures, in: Handbook of Mechanical Systems Design, CRC Press, 2002.

[2] S. H. Juan, J. M. M. Tur, Tensegrity frameworks: Static analysis review, Mechanism and Machine Theory 43 (7) (2008) 859.

[3] C. Sultan, M. Corless, R. E. Skelton, Linear dynamics of tensegrity structures, Engineering Structures 24 (6) (2002).

[4] B. Asgarian, S. Moradi, Seismic response of steel braced frames with shape memory alloy braces, Journal of Constructional Steel Research 67 (1) (2011).

[5] D. J. Miller, L. A. Fahnestock, M. R. Eatherton, Development and experimental validation of a nickel-titanium shape memory alloy self-centring buckling-restrained brace, Engineering Structures 40 (2012).

[6] C. W. Yang, R. DesRoches, R. T. Leon, Design and analysis of braced frames with shape memory alloy and energy-absorbing hybrid devices, Engineering 235 Structures 32 (2) (2010) 498.

[7] N. Mathias, F. Ranaudo, M. Sarkisian, Mechanical amplification of relative movements in damped outriggers for wind and seismic response mitigation, International Journal of High-Rise Buildings 5 (1) (2016) 51.

[8] Amarante dos Santos, F. P., and C. Cismaşiu. "Comparison Between Two SMA Constitutive Models for Seismic Applications." Journal of Vibration and Control. 16.6 (2010): 897-914.

[9] Cismaşiu, C., and F. P. Amarante dos Santos. "Numerical simulation of superelastic shape memory alloys subjected to dynamic loads." Smart Materials and Structures. 17.2 (2008).

[10] Amarante dos Santos, F., and C. Leitão. "Dynamic performance of a superelastic column–base connection." Structural Control and Health Monitoring. 25.7 (2018).

[11] Micheletti, A., FA dos Santos, and P. Sittner. "Superelastic tensegrities: matrix formulation and antagonistic actuation." Smart Materials and Structures. 27.10 (2018).

[12] HAZUS-MH, Multi-hazard loss estimation methodology: earthquake model, FEMA, http://www.fema.gov/hazus (2003).