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A PASSIVE CONTROL SYSTEM BASED ON DOUBLE U-SHAPED METAL ELEMENTS: APPLICATION CASES, DESIGN AND DEVELOPMENTS

Currently, the cumulative damage and poor response of structures subjected to seismic action have gained an increasingly central role in the field of structural engineering, prompting research and development toward Performance-Based Earthquake Engineering. This approach relies on defining multiple performance objectives corresponding to different demand intensities. For this purpose, a new seismic low-damage-based design philosophy is proposed for both structural and non-structural components. Supplementary damping, with or without seismic isolation, is a possible strategy. The presented work, dealing with supplementary damping, will discuss studies and applications of a passive-based hysteretic device, which consists of the combination of two pairs of U-shaped metallic elements that provide either a mono-directional or two-directional dissipative response when two elements are combined appropriately. Hybrid systems can also be conceived, thanks to the versatility of the U-shaped design, allowing integration with supports, shock transmitters, and bracing systems. Past structural-wide applications in bridges and buildings have provided the opportunity to conceive high-performing devices characterized by a wide range of geometry and, consequently, structural capacity in terms of yielding forces, ultimate displacement, and dissipation. The acquired experience has allowed the development of a reliable system validated through experimental tests and nonlinear numerical finite element analyses. The construction sector is highly demanding in terms of cost and time, requiring a fast and reliable methodology for system conception and implementation, triggered by a fast preliminary design. In this framework, the system will be preliminarily described, presenting experimental and numerical studies that led to a closed-form solution for the preliminary design of the device. The application will be discussed, concluding with scheduled future

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developments to be expected in the framework of collaborative research that joins the expertise of the Industry and Academy.

Keywords

Seismic protection, passive control systems, hysteretic devise, design, experimental tests, numerical analyses, applications

1. INTRODUCTION

In the last decades, the socio-economic costs after a seismic event have led to the development of structural ideas aimed at ductile mechanisms activation and brittle mechanisms inhibition, by introducing the Capacity Design [1][2]. A hierarchy of structural and nonstructural components is established, delineating the sequence in which they enter the inelastic range during the response to a ground motion. Components that satisfy the specified criteria, referred to as ductile and among them hysteretic mechanical steel devices can be mentioned as performic technology for new construction realization and the amelioration of existing one. It is important to note that the performance criteria may need to be tailored differently for existing structures and new constructions. However, the overarching goal of minimizing damage and promoting sustainability will continue to guide future implementations. This will necessitate the development of increasingly effective anti-seismic devices, which will include materials with controllable friction, viscous fluids within special mechanisms, viscoelastic polymers, and metals with highly dissipative hysteresis characteristics. The origins of structural control concepts can be traced back to the works of Skinner et al. [3], Housner et al. [4], Soong and Spencer [5], Martinez-Rueda [6]. The pioneering testing of hysteretic dampers began in 1970 at the Physics and Engineering Laboratory in Gracefield, Lower Hutt, New Zealand. Subsequent research efforts have further expanded the field of seismic protection: Roorda [7] conducted tests involving the use of tendons as active bracing systems on small-scale structural models. Kelly and Skinner [8] explored and tested three types of energy absorbers, including U-shaped devices that relied on the bending of flat steel strips, torsional, and flexural predominant devices. “C” shaped devices have been developed and tested by Ciampi and co-workers at the Sapienza University of Rome [9,10]. Dolce et al. (1996) designed and tested a system of U-shaped steel elements radially arranged. Dolce and co-workers [11,12] designed and tested a cover plate for friction joints, thought to force the plasticization into steel shear predominant devices. Building upon these pioneering studies and applications, various damper typologies have been proposed. In the realm of metallic dampers, a recent state-of-the-art study [13] discusses three key aspects: testing procedures, hysteresis behavior, and computational methods. In this context, Somma has conceived, tested (both numerically and experimentally), and patented a steel displacement-dependent device with high versatility for use in a wide range of scenarios. While its application is well established, ongoing developments are required, and cooperation started [14] to support a Ph.D. study on the topic. So that the presented work can be considered the starting point of a synergic contribution between Industry and Academy.

2. DEVICE TECHNOLOGY AND MECHANICAL PRINCIPLES

The hysteretic device (Figure 1a) consists of four appropriately shaped elements interconnected through a central plate and two pairs of external plates. The system (Figure 1b) is here intended as the combination of the device and further connecting elements that serve to integrate the device into part of the construction. It is worth noticing that the interconnecting elements are in turn friction-bolted with central and lateral plates. Further, to reduce load eccentricity, depending on the number of devices, the interconnecting elements can have a different sandwich configuration consisting of two pairs of two interconnecting elements and an internal device or two external devices and one pair of internal interconnection system (Figure 1c). Relative displacements between the two springers of each arch are induced by the push-pulling actions imposed to the central and lateral plates. The induced reactions and internal forces are consequent as respectively reported in Figure 2a and Figure 2b.

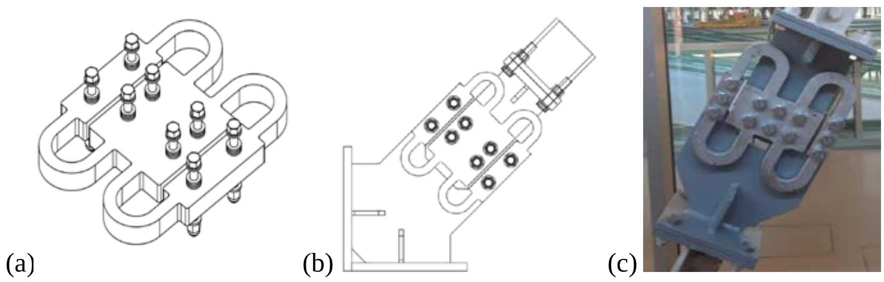

Figure 1. U-Shaped device: representation of device (a) and system (b); real system (c).

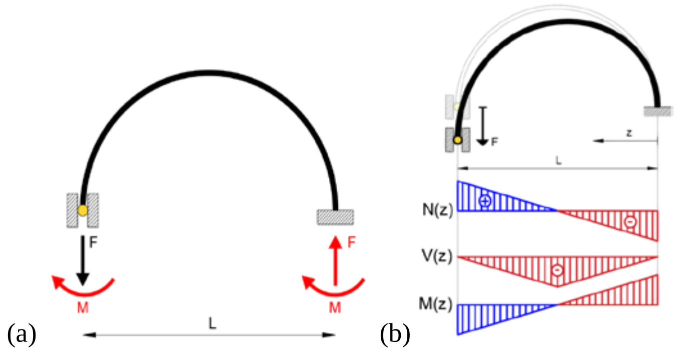

Figure 2. U-Shaped device: a) external reactions; b) internal axial, shear and flexural loads.

The yielding moment (M_y), yielding force (F_y), plastic force (F_p), and the relative displacement at yielding (Δ_y) can be respectively obtained through Equations 1 where: h and t are the arch width and thickness; L is the spring distance and E is the steel young modulus. For a rectangular section, the plastic force F_p is $\approx 3/2$ the yielding force F_y. The elastic stiffness (K_{el}) is consequent as reported in Equation 2. Somma, thanks to past experiences, based on Expressions 1-2, developed a heuristic-based software that predicts the Force-Displacement relationship with a sufficient level of accuracy.

$$M_y = \sigma_y S_{el} = \sigma_y \frac{th^2}{6}\,;\; F_y = \frac{2M_y}{L} = \frac{\sigma_y t h^2}{3L}\;\;;\; F_p = \frac{2M_p}{L} = \frac{\sigma_y t h^2}{2L}\,;\; \Delta_y = \frac{27\pi F_y}{16Et}\left(\frac{L}{h}\right)^3 \tag{1}$$

$$K_{el} = \frac{16Et}{27\pi}\left(\frac{h}{L}\right)^3 \tag{2}$$

Clearly, the arch geometry could be opportunistically shaped to pursue a uniform plasticization of the device, but the gained experiences suggested that the slight reachable improvement is not justifiable when considering the production drawbacks.

3. MECHANICAL TESTS AND NUMERICAL MODELING

Experimental tests are usually performed according to UNI-EN [15] to characterize the mechanical behavior of the material and the system. The first consists of a tensile test conducted on a steel specimen, in order to evaluate the mechanical properties of the material (Figure 3a). A digital Image correlation (DIC) technique, by using Ncorr software [16], was used to better define the local material displacements and deformations (Figure 3b, 3c).

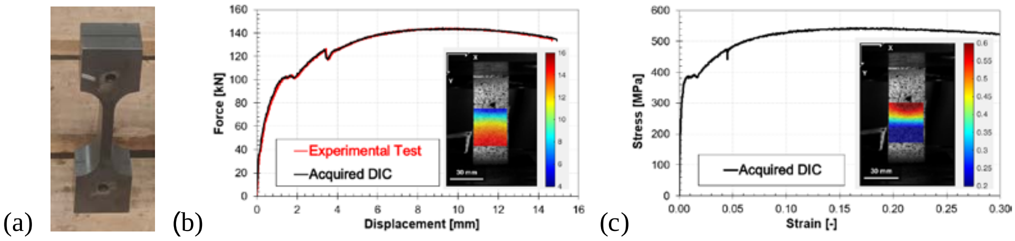

Figure 3. Steel mechanical characterization through Tensile Test: a) Specimen; b) Experimental vs Acquired DIC force-displacement curves; c) Acquired DIC Stress-Strain relationship.

Subsequently, a displacement-controlled procedure is used to define quasi-static cyclic loading consisting of three different displacement levels (25%, 50%, and 100% of the design displacement) with a fixed frequency of 0.05 Hz for the U-shaped device test. Five triangular waveform cycles are conducted for the first two displacement levels, while ten cycles are performed for the last design displacement. Currently, numerical tests are performed through 3D Finite Element Models implemented in ABAQUS [17]. Nonlinear material models are adopted, using a plastic J2 model [18]. An example of FEM model is reported in Figure 4a together with the displacement (mm) (Figure 4b) and stress (MPa) level (Figure 4c). Further, the numerical Force-Displacement is compared (Fig. 5) with the experimental one.

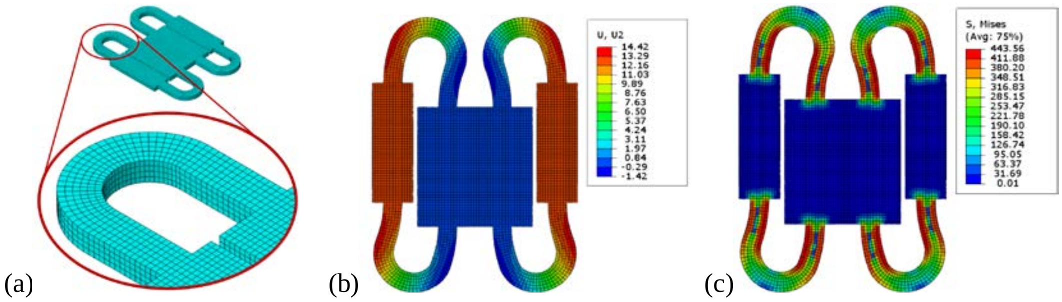

Figure 4. U-Shaped device: Finite Element Modelling: a) FEM mesh; b) Typical deformation due to the displacements applied on the lateral plates; c) Von Mises Stresses due to the displacement load. Geometric features: Arch's Nominal Diameter = 98 mm, Device's Thickness = 20 mm, Arch's Width = 32.5 mm, Device's Total Height = 505.7 mm, Device's Total Width = 365 mm. Adopted properties: Elastic Young's Modulus = 210 GPa, Poisson's 0.3, Initial Yielding Stress = 390 MPa, Q-infinity = 150 MPa, Hardening Parameter b = 5.

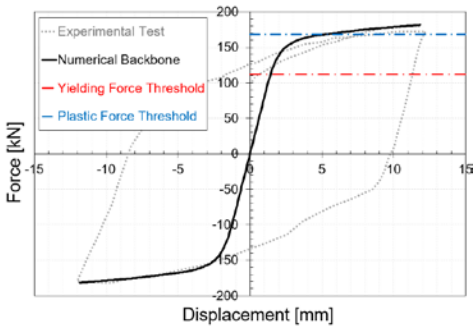

Figure 5. U-Shaped device: Numerical backbone curve modeling results vs Experimental test.

4. REAL APPLICATIONS

The here discussed device can be integrated according to the following configurations: 1) AIOS that, including steel-Polytetrafluoroethylene (PTFE) structural bearing (either spherical or pot-type) can be combined with temporary devices as well as shock transmitters; 2) HBF that are incorporated in bracing systems.

Examples of unidirectional AIOS applications are the viaducts denoted as Ingotte (Figure 6) and Quadrilatero Marche-Umbria (Figure 7); the bidirectional configuration has been adopted for the Aurelia-La Rusca Viaduct (Figure 8). Concerning the Ingotte viaduct, it is worth noticing that the adopted AIOS, having the longitudinal direction of ≈ 1.5 m, supports a vertical load of 9800 kN and has been designed for longitudinal loads and displacements respectively equal to 2600 kN and ± 120 mm. As far as the integration with shock transmitter is concerned, the application on the Picente viaduct can be mentioned (Figure 9). Concerning building applications, HBF has been adopted for the Vibo Valentia school

(Figure 10), the Officine Minganti shopping center (Figure 11), and the Angelini technology hub where a dissipative system is installed externally as reported in Figure 12.

Figure 6. Ingotte Viaduct (Italy) consisting of 4 continuous steel concrete spans. Three AIOS were placed on the central pier and 3×4 longitudinal pot bearings were placed on the abutments and the two lateral piers.

Figure 7. Quadrilatero Marche-Umbria viaducts (Italy). An example of a pair of AIOS working along two orthogonal directions. The project involves the construction of numerous viaducts, all seismically protected with isolators or elastoplastic devices.

Figure 8. Aurelia-La Rusca Viaduct (Italy). The AIOS consists of elastoplastic elements coupled with spherical bearings due the greater rotations in railway applications.

Figure 9. Picente viaduct (Italy). AIOS with shock transmitter. The system consists of a top-placed steel plate connected to the shock transmitter, in turn, connected to the lateral plate of the U-shaped device. In case of slow action (in service), the shock transmitter displacements are allowed, and no force is transmitted to the AIOS. In seismic conditions (dynamic action), the shock transmitter movements are almost restrained, and the AIOS movements are activated.

Figure 10. Vibo Valentia school (Italy). Example of a bracing system with HBF.

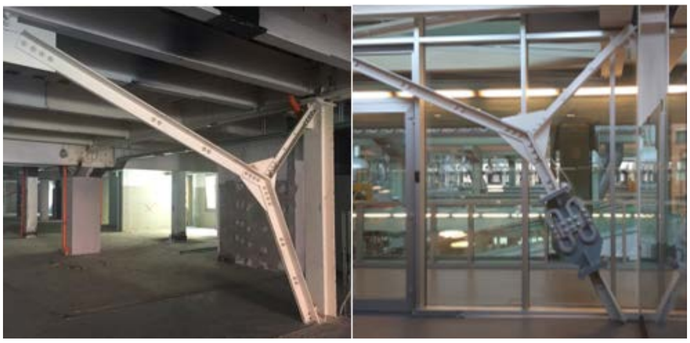

Figure 11. Officine Minganti shopping center (Italy). Bracing before and after the insertion of the HBF dissipative elements.

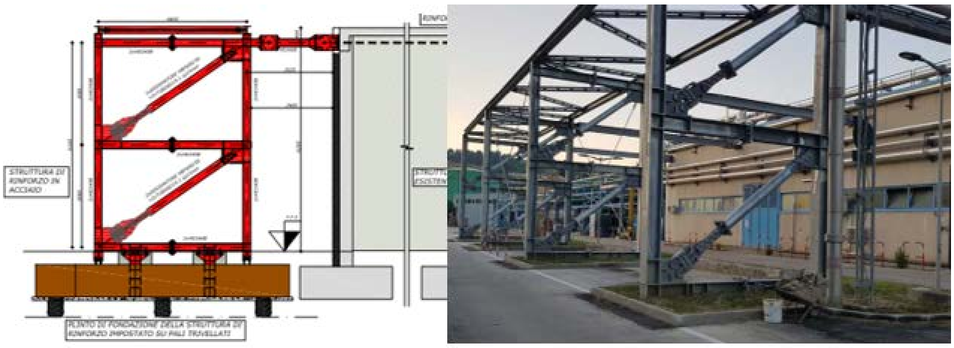

Figure 12. Angelini technology hub (Italy). Dissipative tower connected to the main building.

5. FUTURE DEVELOPMENTS

Developments in technology and structural optimization strategies are currently ongoing to increase the hysteric capacity and optimize the system when low yielding forces are required. Structural optimization strategies will be applied to investigate the performance of new shapes and topologies. The local and global behavior is being studied to better characterize the material and deformations of the device through the use of DIC techniques that can be adopted to process the experimental results and consequently increase the correlation with the numerical models. The research will also focus on aspects of eco-sustainability, aiming to optimize the production process both from the point of view of saving energy and raw materials and of social responsibility.

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