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Original Citation:

Passive energy dissipation enhancement of linear frame structures by the damped cable system / Sorace, S; Terenzi, G. - STAMPA. - 1558:(2013), pp. 2470-2473. (Intervento presentato al convegno 11th International Conference of Numerical Analysis and Applied Mathematics 2013 tenutosi a Rhodes, Greece nel 21-27 September 2013) [10.1063/1.4826041].

Availability:

This version is available at: 2158/835130 since: 2018-03-17T13:08:29Z

Publisher:

T. Simos, G. Psihoyios, C. Tsitouras

Published version:

DOI: 10.1063/1.4826041

Passive Energy Dissipation Enhancement of Linear Frame Structures by the Damped Cable System

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Abstract. The Damped Cable System (DCS) is an innovative seismic protection technology of frame structures that incorporates pre-stressed steel cables linked to fluid viscous spring-dampers fixed to the foundation, at their lower ends, and to the top floor, or one of the upper floors, at their upper ends. The cables have sliding contacts with the floor slabs, to which they are joined by steel deviators. This determines a high-dissipative dynamic coupling between DCS and structure, capable of remarkably enhancing the seismic performance of the latter. An extensive research activity has been developed by the authors on the system, which included laboratory and field testing campaigns, structural modelling and assessment, and the formulation of design procedures. In this paper attention is focused on the finite element model of the DCS, conceived to be easily generated by commercial structural analysis programs, and validated by comparison with the results of the experimental surveys carried out. The model was ultimately updated, and its computational performance is examined by application to a demonstrative case study, constituted by a steel school built in the late 1960s.

Keywords: Added Damping, Passive Energy Dissipation, Advanced Seismic Protection Technologies, Non-linear Fluid-Viscous Dissipaters, Finite Element Modelling, Frame Structures, Seismic Retrofit.
PACS: 46.70.-p

INTRODUCTION

Within the field of passive dissipation technologies for seismic protection of buildings, the Damped Cable System (DCS) [1-2] represents an innovative strategy where structural response is considered with a global approach. As shown in Figure 1, the system includes pre-stressed high-grade steel cables whose lower ends are coupled with pressurized fluid viscous (FV) spring-dampers fixed to the foundation. The unbounded cables have sliding connections (contact being ensured by pre-stress) with the floor slabs, to which they are joined by steel curved deviators specially designed for the purpose. This allows the system counteracting directly the story seismic forces by the horizontal components of the reaction forces exerted by the cables, in addition to the dissipative action produced by the spring-dampers. Moreover, since the cables extend following the horizontal building deflection, a DCS basically exploits the displacements that take place along the complete height of the building, or a significant portion of it (when the upper end is linked to an intermediate floor, and not to the top), rather than the single interstory displacements, as typically occurs in dissipative bracing systems [3-7]. Based on this operational principle, only one spring-damper for each cable—and thus a very limited number of devices—needs being incorporated into the building. The devices can be housed in the basement, which allows carrying out easy inspection, as well as ensuring the highest safeguard of these critical elements.

DAMPED CABLE SYSTEM COMPONENTS

A pre-loaded single-acting (i.e., tension or compression-only reacting) FV spring-damper consists of an internal casing, filled with a compressible silicone fluid, pressurized by a static pre-load F_0 applied upon manufacturing; a piston moving in this fluid; an external casing; and two terminal plates, which connect the device to the supporting structural elements. The operating mechanism is based on the silicone fluid flowing through the annular space existing between the piston head and the internal casing. The inherent re-centering capacity of the device is ensured by the initial pressurization of the fluid. This class of dissipaters has been the subject of a wider research activity developed over the last two decades by the authors, which included also mixed base isolation–energy dissipating FV-based seismic protection technologies [3-12]. A schematic cross section layout of a FV spring-damper is shown in the bottom left image in Figure 1. A typical dynamic response cycle of a single-acting device (tension-only in the

11th International Conference of Numerical Analysis and Applied Mathematics 2013
AIP Conf. Proc. 1558, 2470-2473 (2013); doi: 10.1063/1.4826041

DCS) is sketched in the bottom right image in the same figure, where the bilinear static curve of the spring component is determined by the k_1 and k_2 stiffness values of the response branches situated below and beyond the F_0 pre-load threshold. The $F_d(t)$ damping and $F_{ne}(t)$ non-linear elastic reaction forces of a FV spring-damper can be analytically expressed as [3]:

$$F_d(t) = c \cdot sgn(\dot{x}(t)) \cdot \left|\dot{x}(t)\right|^{\alpha} \tag{1}$$

$$F_{ne}(t) = k_2 x(t) + \frac{(k_1 - k_2)\, x(t)}{\left[1 + \left|\frac{k_1 x(t)}{F_0}\right|^{R}\right]^{1/R}} \tag{2}$$

where parameters k_1, k_2 and F_0 are defined above; c = damping coefficient; sgn(·) = signum function; $\dot{x}(t)$ = device velocity; α = fractional exponent ranging from 0.1 to 0.2; $x(t)$ = device displacement; |·| = absolute value; and R = curvature exponent, normally set as equal to 5.

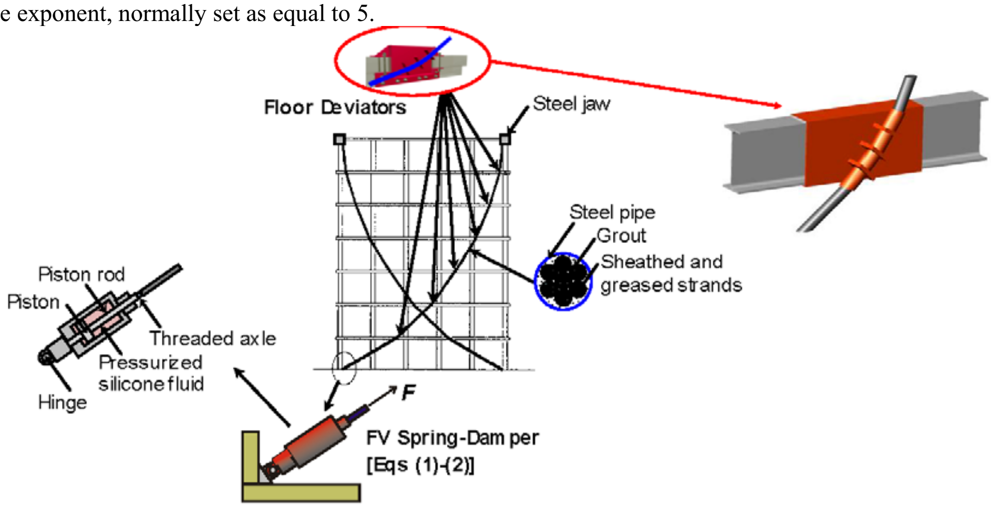

FIGURE 1. Scheme of DCS, including a typical cable section, and a view, a cross section and an idealized response cycle of a pressurized FV spring-damper.

As illustrated in the schematic cross section in Figure 1, a cable consists of greased and sheathed unbonded strands, which are positioned inside a steel duct and grouted therein by cement mortar injections. The strands can move inside relevant pipes, whereas the pipes are blocked by the mortar grout inside the steel duct. In a standard installation of a DCS, the bottom end of the cable is connected to the spring-damper by a threaded steel axle with slots for strand anchoring, whereas the top end is blocked by a steel jaw, usually supported by a cantilever beam connected to the anchoring floor. Assembly consists in pre-loading the spring-damper directly on-site, with the cable already connected to it, and blocked at the upper end. In doing so, the cable is automatically put in tension by the "installation" spring-damper pre-load F_{0d} (which differs from the manufacturing pre-load F_0), and thus the cable pre-stress force F_{0c} is always equal to F_{0d}. The floor–cable contacts are guaranteed by steel deviators, which consist of a steel pipe with the same diameter as the cable duct, which is bent to form a prefixed deviation sector (Figure 1). The deviators transmit the loads exerted by the cable to the crossed beams, and draw its piecewise continuous geometry.

FINITE ELEMENT MODEL OF DCS

Within the finite element model of the Damped Cable system implemented in this study, the cable is reproduced by a series of subsequent elastic beam elements pre-stressed at the design force level F_{0c}, and the spring-dampers by the special assembly shown in Figure 2a. The latter is obtained by putting in parallel, according to the Kelvin rheological scheme, a dashpot (named 1 in Figure 2 a) and a spring (3) element — the reaction forces of which are expressed by equations (1) and (2) —, and a hook"-type element (2) capable of transmitting purely tensile force.

The most critical aspect in modeling a DCS lies in the sliding contact of the cable with the building floors. The simplest way to simulate a contact consists in putting an elastic link between the centre of curvature C_c of the deviator (highlighted in the geometrical layout sketched in Figure 2b) and the cable joint B that simulates the cable–floor contact in deformed conditions. The elastic link constrains B to move along the trajectory determined by the deviator shape, as illustrated in the computational model of the sliding contact schematized in Figure 2c. The action of the cable is transmitted to the floor by the truss element AC_c connecting C_c to the A joint, which represents the contact point in non-deformed configuration. A “body constraint” kinematic condition is assigned to the AC_c truss, so as to impose equal displacements and rotations to A and C_c. The mechanism illustrated in Figure 2c corresponds to a “pulley” effect, which satisfactorily reproduces the real behavior of the cable–floor contact in the absence of friction at the deviator, i.e. the condition assessed by the testing activities carried out on the system [1].

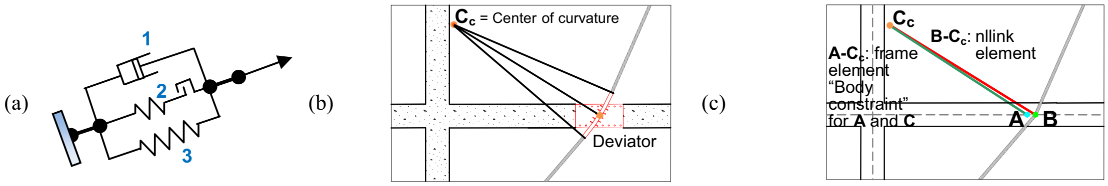

FIGURE 2. Finite element model of a FV single acting (tension-only) spring-damper (a), geometrical layout of a deviator (b), and computational model of relevant cable–floor contact (c).

CASE STUDY APPLICATION

The case study examined herein is a pre-normative steel school structure built in Florence city in the late 1960s. It consists of a two-story central body and two four-story wings, plus an adjacent two-story gym. Figure 3a shows two photographic views of one four-story wing during the demolition of the infills carried out at an early stage of architectural refurbishment works, and relevant viewpoints on the complete finite element model of the buildings, generated by the SAP2000NL commercial calculus program [13].

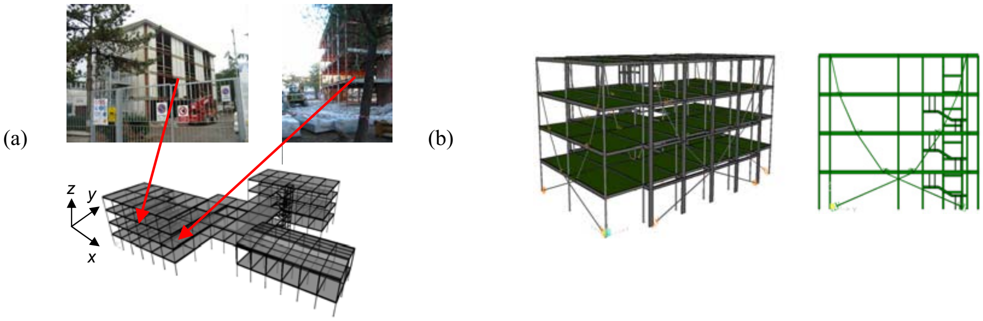

FIGURE 3. Views of the building during the demolition phases of the infills and relevant viewpoints on the finite element model of the original structures (a), and detailed view and cross section of the model incorporating the DCS (b).

A performance-based seismic assessment analysis was developed on the structure in its original conditions, which highlighted that the main structure does not meet the requirement of collapse prevention under the basic design earthquake (BDE, with a 10% probability of being exceeded over 50 years), along its weakest direction in plan (parallel to *x*). Furthermore, it shows the plasticization of a large number of beam-to-column connections and the activation of several plastic hinges in beams and columns, as well as the attainment of maximum transient inter-story drifts of 195.6 mm, with corresponding drift ratios (i.e., the ratios of interstory drifts to story heights) of 5.59%, and maximum permanent drift ratios equal to 2.91%. A slightly better but still very poor performance emerge for the main structure in *y* direction, and for the gym structure. The seismic retrofit hypothesis of the building is based on the incorporation of 6 (along *x*) plus 4 (along *y*) damped cables in the main structure, and 2 plus 2 cables in the gym, as illustrated in the plan drawn in Figure 4a, and the two detailed views of the model in Figure 3b. By way of example of the benefits of the intervention, the maximum interstory drift profiles for the main building in its weakest direction *x* and the BDE level of seismic action are comparatively plotted in the graphs of

Figure 4b, in original and rehabilitated conditions. The 195.6 mm peak drift obtained in unprotected configuration is limited below 51.7 mm , corresponding to a 1.47% drift ratio not exceeding the 1.5% reference threshold for damage control level. Moreover, no plastic activity of beams and columns is noted in the response to BDE, which highlights a very satisfactory performance also in terms of local stress states.

As a consequence of the remarkable seismic improvement of seismic performance caused by the retrofit intervention, only a portion of first and second story columns of the main building needs strengthening. On the contrary, a general strengthening of beams and columns would be necessary in the case of a conventional rehabilitation design (for example, based on the incorporation of a traditional steel bracing system).

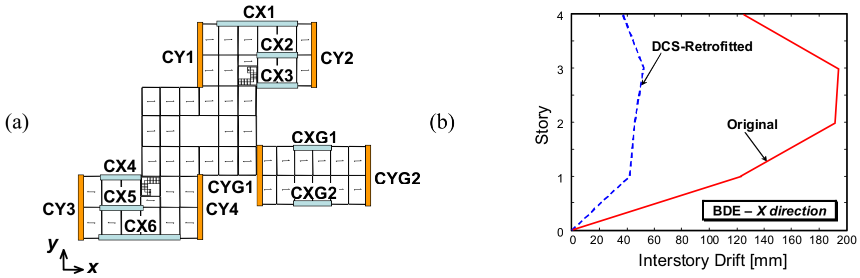

FIGURE 4. Plan distribution of the DCS alignments (a), and maximum interstory drift profiles for the main building in original and rehabilitated conditions (b).

ACKNOWLEDGMENTS

The study reported in this paper was sponsored by the Italian Department of Civil Protection within the Reluis-DPC Project 2010/2013. The authors gratefully acknowledge this financial support.

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