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Modal properties and seismic behaviour of buildings equipped with external dissipative pinned rocking braced frames

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ABSTRACT

This paper deals with the seismic protection of building frames by means of external dissipative systems. Dampers and external framing system can be arranged in several configurations, involving different kinematic behaviours and seismic performances. This study analyses a recently-developed solution called “dissipative tower”, which exploits the rocking motion of a steel braced frame, hinged at the foundation level, for activating the dampers. This system aims at controlling both the global response and the local storey deformation of the frame, by using a reduced number of viscous dampers. A state space formulation of the dynamic problem is presented in general terms, together with the solution of the seismic problem via the modal decomposition method.

A parametric study is carried out to evaluate the influence of the added damping and of the braced frame stiffness on the modal properties and seismic response of a benchmark reinforced concrete frame retrofitted with the external dissipative towers. It is shown that the addition of the towers yields a regularization and reduction of the drift demand along the building height, but it may induce significant changes, not always beneficial, in the distribution of internal actions of the frame and in the absolute storey accelerations.

1. Introduction

Passive damping systems have proven to be very efficient solutions for the seismic protection of new constructions and retrofitting of existing structures [1–4]. Dampers are traditionally installed within a building frame in either diagonal or chevron brace configurations connecting adjacent storeys. This type of damping system, whose effectiveness has been investigated in numerous studies (e.g. [5–11]), presents some disadvantages, particularly when employed for retrofitting existing buildings. Usually, the addition of dissipative diagonal in existing frames provides an increment of axial forces in the columns and this may lead to premature local failures, as observed numerically in the case of moment resisting frames equipped with nonlinear hysteretic dampers [12,13] as well as with linear viscous dampers [14]. In order to avoid this, column strengthening may be required, in the case of existing frames [12], or application of specific capacity design rules, in the case of newly designed moment resisting frames [14]. Furthermore, there may be some feasibility limits on the strengthening of the existing foundations at the base of the bracing system. Also, the indirect costs related to the interruption of the building utilization during the installation of the retrofit system can be very high, particularly for strategic buildings, hospitals or schools.

These problems could be solved efficiently by using external damper configurations, where the dissipative bracings and the relevant foundations are placed outside the construction [15]. External dampers and bracing components can be arranged in very different configurations and the possible solutions can be grouped into three main categories, characterized by substantially different kinematic behaviours, but all permitting the control of both the total amount of the dissipated energy and the frame deformation at the various storeys. In the first arrangement (Fig. 1a), the dampers are placed horizontally at floor level, between the frame and an external stiff structure [16–18]. This way, the links are activated by the relative displacements between the frame and the external structure. A similar configuration can be obtained by placing the dampers between adjacent buildings, though this solution is efficient if the two buildings have strongly different dynamic properties [19–22]. An alternative arrangement consists in coupling the frame with an external shear deformable bracing structure (Fig. 1b). The new and existing structures are connected at the storey level and the dissipative devices, incorporated in diagonal braces within the new

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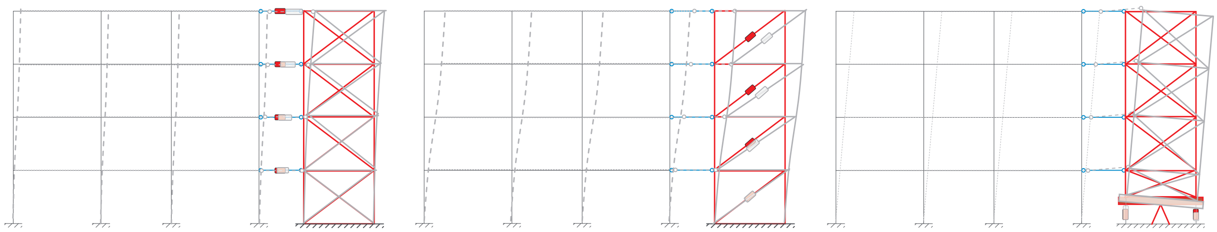

Fig. 1. Illustration of three categories of external dissipative systems: (a) dampers placed horizontally at the storey level between the frame and an external stiff contrasting structure; (b) dampers incorporated within a new shear deformable structure; (c) pinned rocking bracing with dampers located at the base.

structure, are activated by the relative displacements between adjacent floors, as in the more traditional case of dissipative braces placed within the existing structure [3]. A third arrangement, denoted as "dissipative tower" consists in external stiff bracings linked to the frame at the storey level and connected at the foundations by a hinge (Fig. 1c). The energy dissipation is provided by dampers placed at the external frame base and activated by its rocking motion. The high stiffness of the braced frame promotes a uniform distribution of the inter-storey drift of the protected frame. Recently, this system has been employed for the seismic design of new constructions and for retrofitting existing buildings [23,24] and a patent covering a technological solution was registered [25]. A theoretical study [26], in the field of the stochastic dynamic, has compared the performance of this system with that of the system of Fig. 1a).

The rocking motion of structures has emerged in the last few years as an efficient way to reduce seismic damage [27–29], and some studies have also investigated the coupling of existing frames with external rocking structures [30,31]. It is noteworthy that in the literature the term "rocking" is used to describe various configurations, exhibiting different types of behaviour. In general, it is possible to distinguish between "stepping rocking" and "pinned rocking" [32,33]. The first type of rocking denotes structures characterized by an alternation of pivot points, capable of recentering thanks to their self-weight, whereas the second denotes structures rotating about a hinge placed at the foundation level. For example, the dissipative tower of Fig. 1c, which is considered in this paper, can be classified as a "pinned rocking" configuration enhanced with linear fluid viscous dampers. The work of [27] shows that moment-resisting frame can be effectively protected against near-fault ground motion effects by coupling them with pinned rocking walls rather than with fixed-based walls. In [28], rocking wall-frame structures with supplemental draped tendons enhanced with dampers and fuse elements are proposed for the seismic protection of existing buildings. In [29], the results of dynamic tests performed on precast, post-tensioned rocking walls equipped with external dissipative devices are reported. The external devices, located in parallel to post-tensioned tendons, which guarantee recentering, can be fluid viscous dampers, tension-compression yielding steel dampers or a combination of both of them. In [30], external pin-supported walls are used for the seismic retrofit of an eleven-storey steel reinforced concrete frames. Pinned-walls allow to control the displacements distribution, while the seismic performance of the coupled system is enhanced by employing energy dissipative devices. These devices are activated by the rocking motion of the walls and are arranged throughout the building height, between the pinned-wall and the existing column. In [31], the coupling of an existing r.c. frame structure with a light-weight rocking frame equipped with a self-centering energy dissipative steel brace is presented, together with a design method for controlling the story stiffness demand. Dissipative braces located at the base of the rocking frame provide energy dissipation only for moderate or severe seismic actions, whereas for small actions the light-weight rocking frame adds stiffness but no damping to the existing structure.

This study focuses on the coupling of buildings with external dissipative rocking braced frames, centrally pinned at the foundation level, and equipped with dampers activated by the rocking motion. Similarly to pinned-rocking walls [32,33], the proposed system is characterized by a high stiffness, allowing to linearize the displacement distribution along the height of the building and thus enforcing uniform interstorey drifts at the various storeys [34]. However, differently from pinned-rocking walls, it has an enhanced dissipation capacity, thanks to the added viscous dampers, and lower weight, due to the use of steel braces. This is a very important feature, as the self-weight of pinned rocking systems works against stability, thus resulting in large permanent displacements [32,33].

The aim of this study is to investigate the effectiveness of dissipative towers for seismic retrofit of building frames. In particular, complex modal analysis is carried out to study the modal properties of the frame-tower coupled system, and the non-classical damping arising due to the concentration of the viscous dampers at the base of the tower, whereas a modal decomposition technique is employed to evaluate the seismic response of various response parameters while accounting for the contribution of higher order modes. For this purpose, a linear elastic assumption for both the tower and the frame is introduced, which however is accurate only in the case of enhanced performance levels and not very high seismic hazard levels.

This paper is organized in three sections. In the first one, the balance equations governing the linear problem are presented and a state space formulation is adopted to handle the non-classical damping and to obtain a solution of the seismic problem based on the modal decomposition method. The limit solution corresponding to the case of infinitely stiff tower is also discussed, and the properties of a single degree-of-freedom (SDOF) system equivalent to the multi-degree-of-freedom (MDOF) coupled systems are derived, providing an insight into the system vibration and dissipative properties. In particular, the SDOF system properties are obtained by introducing a displacement constraint in the general formulation and they describe the limit case of rigid bracing and rigid floors. The section ends with indications on a procedure that can be applied for the preliminary design of the dissipative devices. The second part of the paper focuses on the modal properties of the coupled system. A benchmark reinforced concrete frame widely analysed in the literature [35–39] is considered to illustrate the system structural properties, and different retrofit configurations are investigated. Two non-dimensional parameters are introduced: the former describes the relative stiffness of the external and protected frame and the latter depicts the added damping. They are used to evaluate the influence of the dissipative bracing characteristics on the dynamic properties of the non-classically damped system at hand. In the last part of the paper, the seismic response of the systems corresponding to the different retrofit scenarios is analysed by using the proposed formulation. The demand parameters considered in the analyses permit to evaluate the effect of the retrofit on the performance of the structural and non-structural building components, as well as of the dampers and the foundations.

2. Problem formulation

The system investigated in this study (Fig. 1c) consists of a building