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Theory of plastic mechanism control for the seismic design of braced frames equipped with friction dampers

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ABSTRACT

An innovative approach for the design of a seismic resistant system composed by the combination of a MR-Frame and a bracing system equipped with friction dampers is presented. From a multi-scale point of view, at local scale, supplementary energy dissipation is provided by means of friction dampers, while, at global scale, the development of a global type mechanism is assured involving all the friction dampers equipping the structure. The activation of all the friction dampers requires an advanced design procedure. Toward this end, the theory of plastic mechanism control, which is based on the application of the kinematic theorem of plastic collapse is extended to the concept of mechanism equilibrium curve, is applied. The fulfillment of the design goal has been pointed out by means of both pushover and dynamic non linear analyses whose results are herein presented and discussed.

1. Introduction

Buildings are normally designed to resist severe earthquakes by dissipating the input energy by means of inelastic deformations occurring in plastic hinges to be developed at beam ends rather than in the columns. Even though such design strategy is able to provide the required safety by dissipating a lot of energy, the damages and the resulting post-earthquake expenses are high. Therefore, in order to reduce the damage to the main structural elements, special devices installed in properly selected places to provide supplementary energy dissipation have been successfully proposed. Passive control devices have been successfully used in structures to reduce their dynamic response when subjected to earthquakes. Within the above framework, friction devices have been mainly proposed because they present low cost and are easy to install and maintain. Several friction dampers have been tested experimentally (Pall and Marsh, 1982; Fitzgerald et al., 1989; Costantinou et al., 1991; Dorka et al., 1998; Gregorian et al., 1993; Nims et al., 1993; Mualla and Belev, 2002) and some of these have been used in buildings around the world. In addition, several researchers developed design procedures for such dampers. In particular, Cherry and Filiatrault (Cherry and Filiatrault, 1990) developed a simple design approach attempting to optimize the slip force in friction damped braced frame structures. Moreschi and Singh (2003) presented a methodology to determine the optimal design parameters for the devices installed at different locations in a building for a desired performance objective. Bhaskararao and Jangid (2006) proposed numerical models of friction dampers for MDOF structures and validated the results. Lee et al. (2008) proposed a design methodology of combined system of bracing and friction dampers.

In this paper an innovative approach for the seismic design of braced frames equipped with friction dampers is presented. It is completely different from design procedures proposed by other researchers (Fu and Cherry, 2000; Ciampi et al., 1995; Kim and Choi, 2005; Garcia and Soong, 2002; Shukla and Datta, 1999; Levy et al., 2001, 2005), because it is based on plastic design. The investigated structural typology belongs to the framework of seismic protection by means of supplementary energy dissipation. In particular, the seismic resistant system can be regarded as a dual system composed of combination of a MR-Frame and a bracing system equipped with friction dampers. Even though this structural scheme is not new, the originality of the work is constituted by the ability in assuring that all the damping devices are effectively involved in the dissipation of the earthquake input energy. To this scope the theory of plastic mechanism control can be applied. Such theory has been developed for the first time with reference to moment resisting steel frames (Mazzolani and Piluso, 1997) and gradually extended to other seismic resistant structural typologies (Faella et al., 1998; Montuori and Piluso, 2000; Mastrandrea and Piluso, 2009; Conti et al., 2009; Longo et al., 2012; Giugliano et al., 2010, 2011) aiming to assure, in all cases, a collapse mechanism of global type. With reference to the structural typology herein investigated, the application of the theory of plastic mechanism control is aimed to assure an energy dissipation mechanism characterized by the activation of all the friction dampers and, in addition, dealing with a dual system, the development of plastic

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hinges at the beam ends. Conversely, columns have to remain in elastic range, with the only exception of base sections of first storey columns. Therefore, from a multi-scale point of view, the seismic performance of the designed structure is governed, on one hand, by the yielding of beam ends and the participation of the friction dampers at the local scale and, on the other hand, by the development of a predefined energy dissipation mechanism at the global scale. The friction dampers are made by a layer of a friction material placed between two steel plates, which accommodate an inner plate with slotted holes allowing the axial displacement of the device. By properly calibrating the stroke of the friction dampers, i.e. the length of the slotted holes, as a function of the displacement demands under destructives earthquakes, it is possible to dissipate the desired energy without any device damage. However, the devices can be easily removed for their maintenance during the service life of the structure or for their substitution. Regarding the proposed design method, it is based on the assumption that beam sections are designed to withstand vertical loads while friction dampers are preliminarily designed according to the storey shear actions due to the design seismic forces. In addition the brace members are designed to prevent buckling and are pinned at their base. Conversely, column sections constitute the unknown of the design problem. The design requirements are derived by means of the kinematic theorem of plastic collapse extended to the concept of mechanism equilibrium curve. Therefore, column sections are obtained by requiring that the mechanism equilibrium curve corresponding to the global mechanism has to lie below those corresponding to all the undesired mechanisms within a displacement range compatible with the stroke of the friction dampers and the local ductility supply of steel members. To evaluate of the accuracy of the presented design method, the seismic inelastic response of a dual system equipped with friction dampers designed according to the proposed method is investigated by means of both push-over analysis and dynamic non linear analyses to check the energy dissipation mechanism actually developed. The multi-scale evaluation of the seismic response is performed, at the global scale, by assessing the energy dissipation mechanism and, at the local scale, by assessing the cyclic response of the friction dampers.

2. Collapse mechanism typologies

The structural typology herein investigated is a seismic resistant system, which can be regarded as, a dual system composed of combination of a MR-Frame and a bracing system equipped with friction dampers. The primary aim of the proposed design procedure is the activation of all the friction dampers and, in addition, dealing with a dual system, the development of plastic hinges at the beam ends and at the base sections of first storey columns only.(Montuori et al., 2014a, 2014b) The number of possible collapse mechanisms for this structural typology is very high, because, at each storey, yielding can develop in friction dampers, beams, columns and bracing members depending on the relative flexural strength of members. Considering that beam and brace sections are previously designed in order to resist vertical loads and out of plan buckling respectively, and that is properly calibrated according to the internal actions due to the design seismic forces, i.e. according to the design storey seismic shear, the problem of plastic mechanism control, is constituted by the evaluation of column sections required, at each storey, to prevent the undesired collapse mechanisms. With reference to the investigated seismic resistant structural system, the collapse mechanism typologies are depicted in Fig. 1 where the global mechanism represents the design goal while all the other mechanisms are undesired.

The design requirements regarding the column sections are derived by means of the kinematic theorem of plastic collapse extended to the concept of mechanism equilibrium curve, by imposing that the mechanism equilibrium curve corresponding to the global mechanism must lie below those corresponding to all the undesired mechanisms within a displacement range compatible with the stroke of the friction dampers and the plastic rotation capacity of the beam ends.

By means of this approach, the theory of plastic mechanism control allows also to include the influence of second order effects. In the following, the mechanism equilibrium curves of the considered mechanisms will be derived with reference to the notation reported in Table 1.

3. Mechanism equilibrium curves

In this section the relationships needed to apply the proposed methodology are reported. To account for second order effects, the kinematic theorem of plastic collapse is extended to the concept of mechanism equilibrium curve. It is the linearization of the softening branch of the behavioral curve $\alpha - \delta$ of the structure, which represents the relationship between the horizontal force multiplier α and the top-sway displacement (Mazzolani and Piluso, 1997), (Longo et al., 2012; Giugliano et al., 2010).

The external work due only to seismic horizontal forces can be always expressed as:

$$W_e = \boldsymbol{F}^T \boldsymbol{s} d\theta \tag{1}$$

The second order external work due to vertical loads can be expressed as (Mazzolani and Piluso, 1997):

$$W_v = \boldsymbol{V}^T \boldsymbol{s} \left(\frac{\delta}{H_0} \right) d\theta \tag{2}$$

According to the first order rigid-plastic theory of the internal work has to be equal to the first order external work so that:

$$W_i = W_e = \alpha \boldsymbol{F}^T \boldsymbol{s} H_0 d\theta \tag{3}$$

Conversely, accounting for second order effects and by denoting with α_c the multiplier of horizontal forces corrected due to second order effects, the balance between external and internal work provides:

$$W_i = \alpha_c \boldsymbol{F}^T \boldsymbol{s} d\theta + W_v \tag{4}$$

which by means of Eqs. (1) and (2), provides:

$$\alpha_c = \alpha - \gamma\delta \tag{5}$$

Eq. (5) constitutes the linearized mechanism equilibrium curve where α is the kinematically admissible multiplier of horizontal forces, according to the first order theory, and γ the slope of the curve given by (Mazzolani and Piluso, 1997):

$$\gamma = \frac{\boldsymbol{V}^T \boldsymbol{s}}{\boldsymbol{F}^T \boldsymbol{s} H_0} \tag{6}$$

In the case of global type mechanism, as shown in Fig. 1, all the storeys participate to the collapse mechanism, therefore the shape vector of the horizontal displacements is given by $\boldsymbol{s}^{(g)} = \boldsymbol{h}$.

The kinematically admissible multiplier of horizontal forces can be expressed as:

$$\alpha^{(g)} = \frac{[\boldsymbol{M}_{c,1}^T I + 2tr(\boldsymbol{B}^T \boldsymbol{R}_b^{(g)}) + tr(\boldsymbol{D}^T \boldsymbol{R}_d^{(g)})]}{\boldsymbol{F}^T \boldsymbol{s}^{(g)}} \tag{7}$$

Furthermore, because all the storeys participate to the global mechanism, H_0 is equal to h_{ns}, and the slope $\gamma^{(g)}$ is obtained from Eq. (6) for $\boldsymbol{s} = \boldsymbol{s}^{(g)} = \boldsymbol{h}$ and $H_0 = h_{ns}$:

$$\gamma^{(g)} = \frac{1}{h_{ns}} \frac{\boldsymbol{V}^T \boldsymbol{s}^{(g)}}{\boldsymbol{F}^T \boldsymbol{s}^{(g)}} \tag{8}$$