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Displacement-based seismic design of hysteretic damped braces for retrofitting in-plan irregular r.c. framed structures

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ABSTRACT

A displacement-based design procedure is proposed for proportioning hysteretic damped braces in order to attain, for the in-plan least seismic capacity direction and a specific level of seismic intensity, a designated performance level of a reinforced concrete (r.c.) irregular framed building to be retrofitted. To this end, a computer code for the nonlinear static analysis of spatial frames is developed to obtain the pushover curve for an assigned in-plan direction of the seismic loads. The town hall of Spilinga (Italy), a two-storey r.c. framed structure with an L-shaped plan built at the beginning of the 1960s, has been considered as case study. Four alternative structural solutions are examined, derived from the first one by the insertion of hysteretic damped braces, considering: the extended N2 and the extended pushover methods combined with a proportional and an inversely proportional in-plan stiffness distributions of hysteretic damped braces. To check the effectiveness and reliability of the design procedure, the nonlinear static response of the unbraced and damped braced frames is compared for different in-plan directions of the seismic loads. Frame members are simulated with a lumped plasticity model, including a flat surface modeling of the axial load-biaxial bending moment elastic domain, while the behavior of a hysteretic damped brace is idealized through the use of a bilinear law. Vulnerability index domains are adopted to estimate the directions of least seismic capacity at the ultimate (i.e. life-safety and collapse prevention) limit states prescribed by Italian and European seismic codes.

1. Introduction

Existing framed buildings that have an asymmetrical plan, in order to comply with architectural and functional requirements, have been one of the most frequently seismically damaged type of structures. Traditional retrofitting techniques for framed structures are based on the widespread strengthening of the structure and/or on the introduction of additional, very stiff, structural members. In recent decades, innovative strategies for the passive control of framed structures have been experimented, such as those based on the insertion of damped braces, connecting two consecutive stories and incorporating energy dissipating devices [3]. The application of such devices to existing buildings is rapidly increasing throughout the world. Several types of both passive and semi-active energy dissipating systems are in use today and new solutions are being proposed and investigated [30,27,1,7,20]. The supplementary damping devices can be classified as: displacement-dependent (e.g. hysteretic damper, HYD), velocity-dependent (e.g. viscoelastic damper, VED) and self-centering (e.g. shape memory alloy damper, SMAD). Moreover, protection technologies for existing buildings based on composite reinforced materials are also available [2,16]. In the present work, attention is focused on metallic yielding hysteretic dampers (HYDs).

For a widespread application of hysteretic damped braces (HYDBs) practical and reliable design procedures are needed. New seismic codes only implicitly allow for the use of these devices (e.g. European code, EC8 2003 [4]; Italian code, NTC08 2008 [9]), while very few codes across the world provide simplified design criteria (e.g. USA code, FEMA 356 2000, [6]). According to the new philosophy of Performance-Based-Design (PBD), a design objective is obtained by coupling a performance level (e.g. operational, immediate occupancy, life-safety or collapse prevention) with a specific level of ground motion intensity (e.g. frequent, occasional, rare or very rare). On the basis of the PBD [21], several simplified nonlinear methods have been proposed, combining the nonlinear static (pushover) analysis of the multi-degree-of-freedom model of the actual structure with the response spectrum analysis of an equivalent single-degree-of-freedom system [5]. More specifically, two alternative approaches have been followed: (a) the Force-Based Design (FBD) approach combined with required deformation target verification [19,10,28]; (b) the displacement-based design (DBD) approach, in which the design starts from a

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target deformation [29,17,18] of an equivalent elastic (linear) system with effective properties (i.e. secant stiffness and equivalent viscous damping).

In this paper, the DBD procedure proposed by Mazza and Vulcano [17], which aims to proportion HYDBs so as to attain a designated performance level of an existing framed structure with a symmetric plan (for a specific level of seismic intensity), is reformulated and extended to in-plan irregular reinforced concrete (r.c.) framed buildings.

2. Nonlinear static analysis of r.c. damped braced structures

A path-following procedure is considered for the nonlinear static analysis of an r.c. spatial damped framed structure subjected, besides the gravity loads, to monotonically increasing horizontal (seismic) loads applied in the center of mass (C_M) of each storey along an assigned direction in plan defined by the angle γ (Fig. 1). At each step of the analysis, the static equilibrium equations is expressed as

$$\boldsymbol{f}[\boldsymbol{u}]-\boldsymbol{p}(\alpha)=0 \tag{1}$$

corresponding to an implicit nonlinear system in the unknown displacement vector $\boldsymbol{u}$, where $\boldsymbol{f}$ represents the structural reaction vector and $\boldsymbol{p}$ the external load vector

$$\boldsymbol{p}=\alpha\hat{\boldsymbol{p}} \tag{2}$$

α being the load multiplier.

In order to avoid convergence problems near the ultimate point of the equilibrium path, an arc-length curvilinear abscissa is assumed to define the $\{\boldsymbol{u},\ \alpha\}$ sequence through fixed step size $\Delta\xi$ in spite of a load control strategy based on a step load $\Delta\alpha$. This results in an additional unknown parameter α, with the arc-length condition

$$\Delta\boldsymbol{u}^T\overline{\boldsymbol{K}}\ \Delta\boldsymbol{u}+\mu\Delta\alpha^2=\Delta\xi^2 \tag{3}$$

representing a circumference of radius $\Delta\xi$ and center in the initial point of the step $\{\boldsymbol{u}^{(k)},\ \alpha^{(k)}\}$, $\overline{\boldsymbol{K}}$ and μ being suitable metric factors (Fig. 1). At each step of the analysis, starting from a trial solution $\{\boldsymbol{u}_j,\ \alpha_j\}$, corresponding to the value of $\Delta\xi$, the increments $\Delta\boldsymbol{u}_j$ and $\Delta\alpha_j$ are defined by

$$\Delta\boldsymbol{u}_j=\boldsymbol{u}_j-\boldsymbol{u}^{(k)};\ \Delta\alpha_j=\alpha_j-\alpha^{(k)} \tag{4a, b}$$

Then, the unknowns $\{\boldsymbol{u}^{(k+1)},\ \alpha^{(k+1)}\}$ can be evaluated through the Newton scheme

$$\boldsymbol{u}_{j+1}=\boldsymbol{u}_j+\dot{\boldsymbol{u}}_j;\ \alpha_{j+1}=\alpha_j+\dot{\alpha}_j \tag{5a, b}$$

As shown in Fig. 1, the solution is found by moving along the tangent to the circumference in $\{\boldsymbol{u}_j,\ \alpha_j\}$, where the iterative corrections $\dot{\boldsymbol{u}}_j$ and $\dot{\alpha}_j$ are obtained as solutions of the linear system

$$\begin{cases}\boldsymbol{r}_j=\boldsymbol{f}[\boldsymbol{u}_j]-\boldsymbol{p}(\alpha_j)=0\\ \Delta\boldsymbol{u}_j^T\overline{\boldsymbol{K}}\ \dot{\boldsymbol{u}}_j+\mu\Delta\alpha_j\dot{\alpha}_j=0\end{cases} \tag{6a, b}$$

The iteration process ends when a suitable measure of the residual equilibrium error $\boldsymbol{r}_j$ (e.g. $\|\boldsymbol{r}_j\|$) becomes less than a prefixed tolerance (e.g. $f_{tol}=10^{-4}$). Further details can be found in a previous work of Mazza [11].

A lumped plasticity model constituted of two parallel elements, one linearly elastic and the other elastic-perfectly plastic, is considered to describe the inelastic behavior of an r.c. frame member [13,14,12]. The elastic component is characterized by the flexural stiffness pEI_r, p being the hardening ratio of the moment-curvature law. The elastic-perfectly plastic component exhibits inelastic deformations, lumped at the end cross-sections (i and j), which are determined with reference to an axial force–biaxial bending elastic domain. Torsional strains are assumed to be fully elastic while shear deformations are neglected. Flat surfaces are used to describe the elastic domain, by considering a piecewise

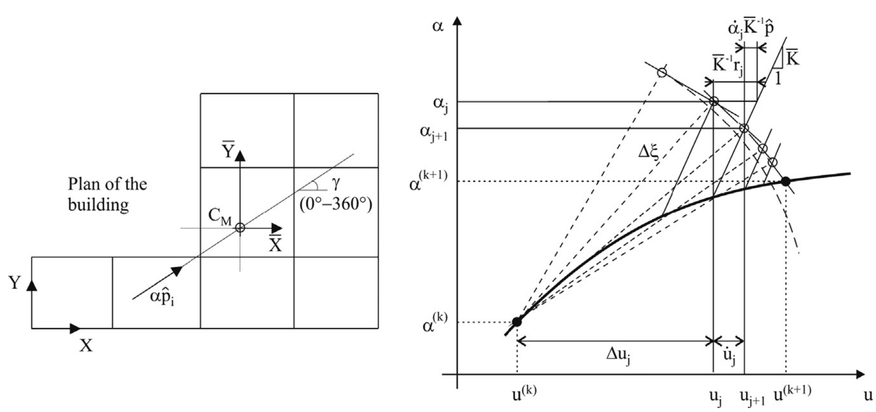

Fig. 1. Nonlinear static analysis of r.c. damped braced structure: arc-length iteration scheme.

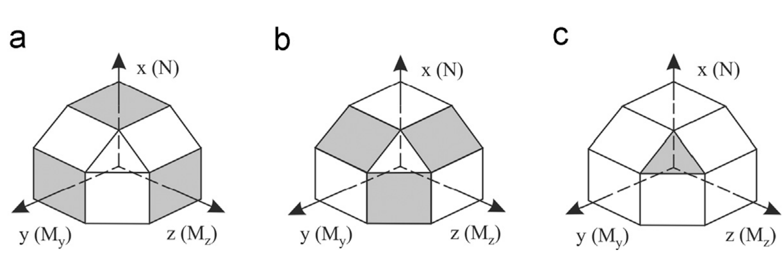

Fig. 2. Flat surfaces approximating the elastic domain of r.c. section.