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Effectiveness of damped braces to mitigate seismic torsional response of unsymmetric-plan buildings

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ABSTRACT

The seismic retrofitting of unsymmetric-plan reinforced concrete (r.c.) framed buildings can be carried out by the incorporation of damped braces (DBs). Yet most of the proposals to mitigate the seismic response of asymmetric framed buildings by DBs rest on the hypothesis of elastic (linear) structural response. The aim of the present work is to evaluate the effectiveness and reliability of a Displacement-Based Design procedure of hysteretic damped braces (HYDBs) based on the nonlinear behavior of the frame members, which adopts the extended N2 method considered by Eurocode 8 to evaluate the higher mode torsional effects. The Town Hall of Spilinga (Italy), a framed structure with an L-shaped plan built at the beginning of the 1960s, is supposed to be retrofitted with HYDBs to attain performance levels imposed by the Italian seismic code (NTC08) in a high-risk zone. Ten structural solutions are compared by considering two in-plan distributions of the HYDBs, to eliminate (elastic) torsional effects, and different design values of the frame ductility combined with a constant design value of the damper ductility. A computer code for the nonlinear dynamic analysis of r.c. spatial framed structures is adopted to evaluate the critical incident angle of bidirectional earthquakes. Beams and columns are simulated with a lumped plasticity model, including flat surface modeling of the axial load-biaxial bending moment elastic domain at the end sections, while a bilinear law is used to idealize the behavior of the HYDBs. Damage index domains are adopted to estimate the directions of least seismic capacity, considering artificial earthquakes whose response spectra match those adopted by NTC08 at serviceability and ultimate limit states.

1. Introduction

In-plan irregularities of buildings due to unsymmetrical layout of the resisting elements can produce significant variations in stiffness, strength and mass distribution, leading to severe seismic vulnerability. In particular, torsional effects adversely affect the nonlinear seismic behavior of reinforced concrete (r.c.) framed buildings leading to premature failure [1]. Moreover, torsional response makes the seismic retrofitting of unsymmetric-plan buildings more complicated than for symmetric ones. A wide variety of new technologies is available for controlling earthquake induced torsion of irregular buildings, referring to base isolation [2] and/or supplemental damping [3,4]. Specifically, base-isolation allows a considerable reduction of the horizontal seismic loads transmitted to the superstructure, increasing the fundamental vibration period of the base-isolated structure, to shift it in the range of low spectral accelerations (e.g. elastomeric bearings), or

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limiting the maximum force transmitted to the superstructure, depending on the friction coefficient (e.g. curved surface sliding bearings). However, torsional amplification of base-isolated structures can be significant, depending on superstructure eccentricity and lateral-torsional flexibility of both the superstructure and base isolation system [5,6]. Alternatively, the seismic retrofitting of unsymmetric-plan buildings can be easier and less expensive using passive control systems based on the incorporation of steel braces connecting two storeys and equipped with displacement- (e.g.: friction damper, FRD; metallic-yielding hysteretic damper, HYD) or velocity-dependent (e.g.: viscoelastic damper, VED; viscous damper, VSD) nonlinear devices [7,8]. Moreover, the tuned mass damper (TMD) represents a simple and reliable passive control system, which is applicable not only in new constructions but also existing ones [9].

In Europe, current seismic codes only implicitly allow for the use of such energy dissipating devices (e.g. European code, EC8 [10]; Italian code, NTC08 [11]), while worldwide very few seismic codes provide for simplified design criteria of DBs (e.g. USA code, FEMA 356 [12]). Several simplified nonlinear design methods of damped braces (DBs), combining the nonlinear static (pushover) analysis of the multi-degree-of-freedom (MDOF) model of the actual structure with the response spectrum analysis of an equivalent single-degree-of-freedom (ESDOF) system, have been proposed for the seismic retrofitting of regular r.c. framed structures [13–18]. However, only few design procedures of DBs, based on the nonlinear behavior of the frame members, have been proposed for an in-plan irregular framed structure [19–22]. The aim of the present work is to evaluate the effectiveness and reliability of a Displacement-Based Design (DBD) procedure of hysteretic dissipative braces (HYDBs). To this end, a revised expression of the equivalent viscous damping is assumed by considering the hysteretic energy dissipated by a damped braced frame under bidirectional seismic loads, where corrective factors are considered as a function of design parameters of the HYDBs. Moreover, the extended N2-method considered by EC8, which adopts correction factors based on elastic modal analysis to evaluate the higher mode torsional effects, is used to improve the nonlinear response obtained by the standard pushover analysis [23].

The case study focus on 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 [24]. This building designed in line with a former seismic code [25], for a high-risk seismic zone, is retrofitted by the incorporation of HYDBs to attain performance levels imposed by NTC08. To avoid brittle behavior of the r.c. frame members, different design values of the frame ductility are considered in combination with a constant design value of damper ductility. Moreover, to eliminate (elastic) torsional effects, inversely proportional in-plan stiffness distribution of the HYDBs is assumed. Artificially generated ground motions, whose response spectra match those adopted by the Italian seismic code for different seismic intensity levels, are considered to compare the nonlinear dynamic response of the original and retrofitted structures for different in-plan directions of bidirectional ground motion varying in the range 0–360°, with a constant step of 15°. A lumped plasticity model describes the inelastic behavior of r.c. frame members, including a 26-flat surface modeling of the axial load-biaxial bending moment elastic domain at the end sections where inelastic deformations are expected [20]; a bilinear model idealizes the nonlinear response of the HYDBs. Damage index domains of r.c. frame members and HYDBs are adopted to evaluate the directions of least seismic capacity at the serviceability and ultimate limit states provided by NTC08.

2. DBD procedure of damped braces for unsymmetric-plan structures: theory

A DBD iterative procedure of dissipative braces, which is both conceptually clear and simply to apply, is proposed for the seismic retrofitting of in-plan asymmetric r.c. framed structures. More specifically, a six-step DBD design procedure of HYDBs is explained below.

2.1. Extended N2-method for pushover analysis along the principal directions of the in-plan irregular unbraced frame

The aim of the extended N2 method is to take into account the higher mode torsional effects of in-plan irregular framed structures (UF, Fig. 1a), by modifying the lowest base shear-top displacement capacity curves ($V^{(F)}$-d) along the X and Y directions. The most common lateral-load profiles are considered for the unbraced frame (UF): e.g. a “uniform” distribution, proportional to the floor masses (m_1, m_2,.., m_n); a “triangular” distribution, obtained by multiplying the first-mode components (ϕ_1, ϕ_2,.., ϕ_n) by the corresponding floor mass. The correction factors, evaluated for each horizontal direction (i.e. CF_γ, $\gamma \in (X,Y)$), are defined as the ratio between the normalized top displacements obtained by elastic modal analysis and nonlinear static analysis [23]. The normalized top displacement is defined as the top displacement at an arbitrary in-plan location (e.g. the six corner points shown in Fig. 1a) divided by the corresponding value at the center of mass (C_M). It should be noted that the correction factors are assumed equal to or greater than 1.0.

2.2. Definition of an equivalent two degrees of freedom (ETDOF) system of the unbraced frame (UF) along the principal in-plan directions

The selected $V_\gamma^{(F)}$-d_γ curves ($\gamma \in (X,Y)$) can be idealized as bilinear and the original frame can be represented by an equivalent two degrees of freedom (ETDOF) system characterized by a bilinear curve (V_γ^*-d_γ^*), with a yield displacement $d_{yl,\gamma}^{(F)}$ and a stiffness hardening ratio r_F, derived from the idealized $V_\gamma^{(F)}$-d_γ curve (Fig. 2). For a given level of performance, the displacement ($d_{p,\gamma}$) is evaluated as function of an assigned value of the frame ductility