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Assessment of capacity design of columns in steel moment resisting frames with viscous dampers

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ABSTRACT

Previous research showed that steel moment-resisting frames (MRFs) with viscous dampers may experience column plastic hinges under strong earthquakes and highlighted the need to further assess the efficiency of capacity design rules. To partially address this need, three alternatives of a prototype building having five, 10 and 20 stories are designed according to Eurocode 8 using either steel MRFs or steel MRFs with dampers. Incremental dynamic analysis (IDA) is conducted for all MRFs and their collapse resistance and plastic mechanism is evaluated. The results show that steel MRFs with dampers are prone to column plastic hinging in comparison to steel MRFs. The steel MRFs with dampers are then iteratively re-designed with stricter capacity design rules to achieve a plastic mechanism that is approximately similar to that of steel MRFs. The performance of these re-designed steel MRFs with dampers indicates, that overall, enforcement of stricter capacity design rules for columns is not justified neither from a collapse resistance or a reparability perspective.

1. Introduction

Conventional seismic-resistant steel structures may experience significant structural and non-structural damage under strong earthquakes due to large story drifts and cyclic plastic deformations in main structural members [1]. Damage results in socio-economic losses (e.g. large repair costs and loss of building occupancy), which are no longer acceptable by modern societies aiming to achieve high levels of earthquake resilience. Therefore, there is an urgent need for codification and widespread implementation of resilient seismic-resistant steel structures that are less vulnerable and easier to repair after strong earthquakes [2].

A well-known class of resilient steel structures is the steel moment-resisting frames (MRFs) with passive dampers [3]. Among the different types of dampers, fluid viscous ones have been extensively studied as they have major advantages including large energy dissipation capacity and peak forces that are out of phase with the peak story drifts of elastic or mildly inelastic frames [4]. Viscous dampers consist of a hollow cylinder fully filled with a fluid and a steel piston with a rod and a piston head. Based on previous dynamic tests, the hysteretic behavior of viscous dampers can be described by [4]:

$$F_D = C \cdot |v|^{\alpha} \cdot \mathrm{sgn}(v) \tag{1}$$

where F_D is the damper force output, C is the damping coefficient, v is the velocity across the damper, a is the velocity exponent, and sgn is the signum function. Viscous dampers are typically inserted in steel MRFs by using strong supporting braces, which are designed to be stiff enough so that story drift produces damper deformation rather than brace deformation [3].

A parametric study on the seismic response of yielding single-degree-of-freedom (SDOF) systems evaluated the effect of supplemental viscous damping on peak displacements, residual displacements and absolute accelerations [5]. Researchers proposed predictive formulae for the peak relative velocity of yielding SDOF systems for different levels of supplemental viscous damping [6], while others showed that the nonlinearity of the viscous damper influences the probabilistic seismic response of linear elastic SDOF systems [7,8]. Research efforts quantified the benefits of using viscous dampers for reducing damage in non-structural components of building structures [9,10]. Notable experimental studies that validated the superior seismic performance of steel MRFs with viscous dampers include the full-scale shaking table tests conducted by Kasai et al. [11] and the large-scale real-time hybrid simulations conducted by Dong et al. [12].

ASCE 7-10 provides a detailed design procedure for buildings with passive dampers within the framework of the traditional response spectrum and equivalent lateral force methods of analysis [13]. These procedures are iterative and their basis is the use of an equivalent highly damped linear elastic SDOF system, which serves as a substitute of the real yielding frame with dampers. The use of the equivalent linear SDOF system allows the damping system (i.e., the frame that includes the viscous dampers, and their

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supporting braces and connections) to be designed for three different loading conditions, i.e. those associated with the maximum displacement, maximum velocity and maximum acceleration. The effectiveness of the ASCE 7-10 procedure has been extensively evaluated with seismic simulations on steel MRFs with viscous dampers under the design basis and maximum considered earthquake (DBE and MCE, respectively) intensities in [14,15]. Guo and Christopoulos [16] proposed an alternative design procedure for multiple target performance objectives utilizing a graphic tool to estimate peak response parameters of yielding structures with passive dampers either by nonlinear response history analyses or by an equivalent linearization procedure.

The author and co-workers explored the design requirements (base shear strength, design drift) which guarantee that a steel MRF with viscous dampers will have seismic collapse resistance similar or higher than that of a special steel MRF [17]. Moreover, they showed that the collapse mode of steel MRFs with viscous dampers is generally identical to that of a special steel MRF, i.e. a sway mechanism with plastic hinges in beams and in column bases. In some cases though, the collapse mode was a combination of plastic hinges in beams and plastic hinges in columns of different stories. Interestingly, a collapse mode characterized by a distinctive soft-story mechanism (i.e. formation of plastic hinges at the top and bottom of columns for a particular story) was also observed for few ground motions (e.g. three out of 44 records). The reason of these unique (for a steel MRF) collapse modes is the high viscous dampers forces that impose high axial force demands to the columns. The aforementioned study, which was based only on a 5-storey building, highlights the need for further research on capacity design of columns and its effect on the collapse resistance of steel MRFs with viscous dampers. Moreover, the seismic intensity beyond which plastic hinges are developed in columns of steel MRFs with viscous dampers should be evaluated since column plastic hinges lead to non-reparable damage, while repair of damage in beam plastic hinges can be addressed by using special bolted fuses at the beam ends [18,19].

This paper aims to partially answer the research questions raised in the previous paragraph by evaluating the efficiency of the capacity design of columns for three steel MRFs with viscous dampers. Three alternatives of a prototype building having five, 10 and 20 stories are designed using either steel MRFs or steel MRFs with viscous dampers. The steel MRFs with viscous dampers are designed to have significantly higher performance than that of the steel MRFs. Incremental dynamic analyses (IDA) [20] under 44 ground motions are conducted for all the frames and their collapse resistances and plastic mechanisms (with a focus on column plastic hinges) under different drift levels are evaluated and compared. The results show that tall steel MRFs with viscous dampers are prone to column plastic hinging in comparison to steel MRFs. The steel MRFs with viscous dampers are then iteratively re-designed to achieve a plastic mechanism that is approximately similar to that of the steel MRFs. The performance of the redesigned frames is assessed with IDA and the results are quantitatively and qualitatively evaluated to explore whether there is a need for stricter capacity design rules for columns of high-performance steel MRFs with viscous dampers.

2. Prototype building and design of seismic-resistant frames

2.1. Prototype building

Fig. 1 shows the plan view of a prototype 5-bay by 3-bay steel office building. Three alternatives of this building having five, 10 and 20 stories (as shown in Fig. 2) are considered. The building has two perimeter 3-bay seismic-resistant MRFs in the longitudinal

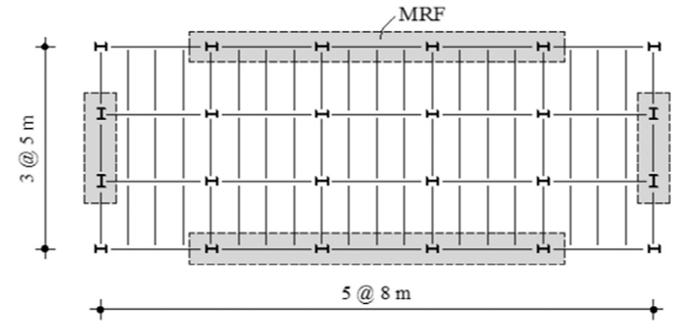

Fig. 1. Plan view of the prototype building.

direction and two perimeter 1-bay seismic-resistant braced frames in the transverse plan direction. This study focuses on the design of one of the perimeter MRFs in the longitudinal direction. This perimeter MRF is designed as a steel MRF according to Eurocode 8 (EC8) [21] and as a steel MRF with linear viscous dampers.

The models used to perform the designs are based on the centerline dimensions of the steel MRFs without accounting for the finite panel zone dimensions. Beam-column connections are assumed to be rigid, while a rigid diaphragm constraint is imposed at the nodes of each floor to account for the presence of the composite slab. Moreover, a 'lean-on' column is included in the models to account for the P-Δ effects of the gravity loads acting in the tributary plan area (i.e. half of the plan area for one perimeter steel MRF).

2.2. Design of steel MRFs

The steel MRFs without viscous dampers are designed as high-ductility class according to EC8 [21]. The DBE is expressed by the type 1 EC8 design spectrum for peak ground acceleration equal to 0.35g, ground type B, importance factor II, and behavior factor q equal to 6.5. The steel grade for columns is S355 and for beams is S275. To meet the damage limitation requirement given ductile non-structural elements, the allowable peak story drift, θ_{max}, under the frequently occurred earthquake is equal to 0.75% [21]. The frequently occurred earthquake has an intensity of 40% the DBE, i.e. the ν reduction factor is equal to 0.4 according to EC8 [21]. For all the steel MRFs, the story drift sensitivity coefficient θ that accounts for P-Δ effects is limited below 0.20. The weak beam-strong column capacity design rule is enforced by satisfying the condition

$$\sum M_{RC} \geq 1.3 \cdot \sum M_{Rb} \tag{2}$$

where ΣM_{RC} is the sum of the plastic moments of resistance of the columns (considers the effect of the axial force in the column) framing a joint and ΣM_{Rb} is the sum of the plastic moments of resistance of the beams framing the same joint.

All designs comply with the specific rules of EC8 for steel MRFs. In particular, the design axial forces in beams are less than 15% of their plastic axial resistance, the design shear forces in beams are less than 50% of their plastic shear resistance, and the design shear forces in columns are less than 50% of their plastic shear resistance. The columns are also checked against axial forces, bending moments and shear forces calculated according to [21]:

$$N_{Ed} = N_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \Omega \cdot N_{Ed,E} \tag{3}$$

$$M_{Ed} = M_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \Omega \cdot M_{Ed,E} \tag{4}$$

$$V_{Ed} = V_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \Omega \cdot V_{Ed,E} \tag{5}$$