Engineering Structures 116 (2016) 192–202

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic fragility estimates of a moment-resisting frame building controlled by MR dampers using performance-based design

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ARTICLE INFO

Article history:
Received 25 April 2014
Revised 27 February 2016
Accepted 29 February 2016
Available online 12 March 2016

Keywords:
Fragility analysis
Performance-based design
Magnetorheological damper
Multi-objective
Genetic algorithm
High-rise building

ABSTRACT

Seismic fragility was estimated for a controlled high-rise building using 200 kN magnetorheological (MR) dampers with direct performance-based design (DPBD) to assess seismic vulnerability and to validate the performance of the DPBD which was previously developed. The DPBD offers multiple control design layouts for various performance levels subjected to different hazard levels using multi-objective optimization approaches. These multiple control design layouts for the given performance levels need to be validated using random seismic excitations because those performance-based designs (PBD) had been devolved based on the specific strength of design objective earthquakes (i.e., hazard levels) from the DPBD. In order to evaluate those PBD cases using MR dampers, two different approaches for fragility estimation of the four PBD cases under two hazard levels are conducted: traditional approach using the overall maximum interstory drift and system reliability approach which considers multiple limit states associated with the maximum interstory drift for stories within the entire system. The results are compared using 41 earthquake ground motions. From this study, overall seismic fragility relations have been derived from extensive fragility analyses in terms of broad range of hazard levels for multiple performance levels which were achieved by new direct performance-based design using MR dampers. Moreover, it is observed that the multiple performance-based control design cases obtained from DPBD clearly show significant reduction in seismic vulnerability compared to the uncontrolled case. It also shows different seismic fragility estimates against seismic hazards reflecting the performance enhancement based on the initial objective of the DPBD. Based on the results, the system reliability approach can identify the stories that have close interstory drifts to the overall maximum value allowing for more accurate estimates of the seismic fragility of multi-story buildings.

1. Introduction

Seismic hazard mitigation of civil structures has been one of the hot topics and challenging research areas during the last several decades. Performance-based design (PBD) is one of the most well-investigated approaches to carry out structural seismic designs to sustain structural safety about a specific hazard level. The basic concepts of the PBD is that size, type, or material properties of structural members are designed and determined to satisfy the predefined performance level about the predefined hazard level. Most PBD approaches are focused on a single performance level about single hazard level [1–4]. The single performance level should be achieved in terms of single objective which is generally defined as total weight of a structure. The structural member sizes are optimized to minimize the objective and satisfy performance level using optimization algorithms [4]. Multi-objective optimization algorithms also applied for the PBD for the moment-resisting civil steel structures such as multi-objective genetic algorithms [5], simulated annealing methods [6], tabu search methods [7], and the combinational approaches [4]. In order to solve engineering problems, reliability-oriented single and multi-objective optimization techniques have been developed and applied [8–10]. In all the studies cited above, the performance-based designs are only limited to structural member optimization to satisfy the predefined performance levels.

As another approach for the seismic mitigation of civil structures, structural control devices have been developed with 4 different categories: passive control devices [11,12], active control devices [13], semi-active control devices [14–16], and hybrid control approaches [17]. These control devices have been also used for

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http://dx.doi.org/10.1016/j.engstruct.2016.02.055
0141-0296/

PBD to satisfy performance level by installing control devices to reduce structural responses instead of changing structural member sizes and material types [18–20]. However, most of these investigations are limited to satisfy a predefined performance level about a specific hazard level, and locations and number of the control devices were not optimized, even though the performance of the control devices is highly dependent on the location and number of devices in each story of the building [21–23]. Thus, in order to achieve enhancement in performance of the PBD using control devices with minimum cost, optimal locations and number of control devices should be considered as variables of the performance-based design. Furthermore, these optimal design layouts are also highly dependent on the objective performance level and its hazard level. Thus, Cha et al. [24] proposed a cost-effective direct performance-based design (DPBD) method using multi-objective optimization to find multiple optimal control device layouts which satisfy multiple performance levels (PLs) subjected to multiple hazard levels (HLs) simultaneously with Pareto optimal concept. This DPBD uses one objective earthquake to find optimal layouts of the control devices for the performance-based design. However, extensive vulnerability evaluation of the cases of the performance-based design has not been carried out based on random seismic events.

Seismic fragility analysis can be a tool to estimate vulnerability of structural systems under natural hazards. It plays an important role in estimating seismic losses and in the decision making process based on structural performance during seismic events. A number of research studies related to seismic fragility analysis and the methodology of developing fragility curves for building structures have been actively conducted [25–29]. To develop seismic fragility curves, structural capacity limits and demand models are needed. For constructing demand models, the overall maximum interstory drift over the height of a building has been widely used as typical demand measure in these studies. The overall maximum interstory drift is a convenient measure to describe the structural response of a building to lateral loads. However, for multi-story buildings, fragility estimates developed using only the overall maximum interstory drift may not reflect the actual vulnerability of a building, especially when the interstory drifts for one or more stories are close to the maximum value [30]. This is because there is only one limit state function defined based on the overall maximum interstory drift. To assess the probability that any interstory drift exceeds a specified limit for a given structural performance level, it is important to include more limit state functions associated with the specific drift demand for stories within the entire system. To estimate the reliability of a system that is composed of multiple components, not only the reliabilities of individual components, but also the uncertainties and correlation that may exist among the components should be considered [31]. Hence, in this study, overall fragility relationships in terms of broad hazard levels use a system reliability approach which can address multiple stories of controlled structures equipped by MR dampers based on newly recently proposed PBD method which offers design sets satisfying multiple performance levels subjected to multiple hazard levels.

2. Backgrounds

2.1. Semi-active magnetorheological damper

To date, the performance of the magnetorheological (MR) dampers are well proved from large-scale real time hybrid simulations [32–33]. Moreover, damping performances under various types of time-delay in MR dampers (including control systems) were extensively studied [34]. Consequently, for the DPBD approach, MR dampers are used as a control device. The capacity of the nominal control force is approximately 200 kN at a control current 2.5 A to the damper wire coils. High nonlinear behavior of the MR damper is described by the phenomenological model developed by Spencer et al. [35]. The detailed information of the optimal parameters of this model can be found in Phillips and Spencer [36], and MR damper is expressed as,

$$c_1\dot{y} = \alpha z + k_0(x_d - y) + c_0(\dot{x}_d - \dot{y}) \tag{1}$$

$$\dot{z} = -\gamma|\dot{x}_d - \dot{y}|z|z|^{n-1} - \beta(\dot{x}_d - \dot{y})|z|^{n-1} + A(\dot{x}_d - \dot{y}) \tag{2}$$

$$f = \alpha z + c_0(\dot{x}_d - \dot{y}) + k_0(x_d - y) + k_1(x_d - x_0) \tag{3}$$

where αz is force determined by the evolutionary variable z, f is the restoring force, c_1 is included to produce the roll-off observed at low velocities, c_0 indicates the viscous damping, k_0 represents the stiffness at large velocities, k_1 is related to the nominal damper force due to damper accumulator, x_0 is the initial displacement of the spring of the MR damper model. For the maximum current of MR damper, 2.5 A is used for the Passive-On (PSON) control.

2.2. Direct performance-based design procedure

Unlike the traditional performance-based design method, direct performance-based design (DPBD) [24] can find multiple control design layouts to satisfy multiple performance levels subjected to multiple hazard levels. Using a smart damping system (i.e., MR dampers), the multiple performances can be achieved by optimally installing without any change of the member sizes of the structure subjected to multiple hazard levels. A set of the PBD options that satisfy multiple performance objectives is obtained by multi-objective optimization genetic algorithms (MOGAs) [21–23] which allow a tradeoff among all predefined conflicting design objectives in a Pareto-optimal sense. The procedure of the DPBD is,

1. Development of numerical models of the structure and control device to carry out dynamic nonlinear time history analyses.
2. Determination of the multiple performance levels under multiple hazard levels based on spectral response acceleration parameters from seismic hazard maps. By modifying spectral acceleration based on site class effects, response spectrum is developed. As an objective earthquake, El Centro earthquake is used. The objective earthquake for each hazard level is scaled to maximum considered earthquake and design-based earthquake using spectral acceleration parameters calculated based on site class and damping ratio of the structure location.
3. In order to find Pareto-optimal solutions (i.e., multiple layouts of the control devices) satisfying multiple design objectives and multiple performance levels simultaneously, multi-objective optimizations are carried out using gene manipulation genetic algorithms (GMGAs) developed by Cha et al. [19]. Parallel computing methodologies are used for multiple hazard levels to explore Pareto-optimal solutions. The two objective functions are formulated using nonlinear dynamic equations of motions of the structure including location and numbers of MR dampers.
4. Integration of multiple Pareto-optimal curves for multiple hazard levels into one Pareto-optimal solution set. Using the combined Pareto-optimal solutions, the final performance-based designs will be selected to satisfy multiple performance levels and hazard levels.
5. GMGAs are continued until all predefined performance levels are satisfied.
6. Validation of performance of the selected design solution by nonlinear time history analyses using a set of historical earthquakes having diverse frequency content and magnitudes.