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A modified DEB procedure for estimating seismic demands of multi-mode-sensitive damage-control HSSF-EDBs

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ABSTRACT

The core objective of this research is to develop a modified dual-energy-demand-index-based (DEB) procedure for estimating the seismic demand of multi-mode-sensitive high-strength steel moment-resisting frames with energy dissipation bays (HSSF-EDBs) in the damage-control stage. To rationally quantify both the peak response demand and the cumulative response demand which are essential to characterise the damage-control behaviour of the system subjected to ground motions, the energy factor and cumulative ductility of modal single-degree-of-freedom (SDOF) systems are used as core demand indices, and the contributions of multi-modes are included in the proposed method. A stepwise procedure based on multi-mode nonlinear pushover analysis and inelastic spectral analysis of SDOF systems is developed. Based on the numerical models validated by test results, the proposed procedure is applied to prototype structures with a ground motion ensemble. The satisfactory agreement between the estimates by the proposed procedure and the results determined by nonlinear response history analysis (NL-RHA) under the ground motions indicates that the modified DEB procedure is a promising alternative for quantifying the seismic demands of tall HSSF-EDBs considering both peak response and cumulative effect, and the contribution of multi-modes can be reasonably estimated.

1. Introduction

A fundamental objective of conventional seismic design is to ensure the survival of a structure under earthquake ground motions for fulfilling the life-safety purpose. In this context, practical seismic design methodologies are generally governed by ductility-based philosophy that pursues sufficient inelastic deformation and stable plastic energy dissipation of a structure. To survive a moderate-to-strong earthquake attack, the members and connections of a conventional steel moment-resisting frame (MRF) are allowed to enter the inelastic stage in rapid succession. Notwithstanding the satisfactory ductility and stable energy dissipation capacity of conventional steel MRFs, recent seismic loss estimations show that unacceptable post-earthquake damages and residual deformations [1,2] induced by the inelastic actions of structural members may result in long-time occupancy suspension for repairing works. For structures experiencing severe damages, complete demolition and re-construction are unavoidable, which can lead to substantial economic loss. In order to enhance the seismic resilience [3,4] of steel MRFs, the idea of developing innovative steel MRFs showing improved damage evolution mode and encouraging post-earthquake performance is attracting interests from research communities.

Recently, the concept of "hybrid-steel-based" [5,6] or "dual-steel-based" [7–10] steel MRFs was found to be promising for improving the seismic performance of steel MRFs. In particular, appropriate combination of structural elements of relatively lower strength (e.g. low-yield-point steel or mild carbon steel) with high-strength steel (HSS) members can decouple the inherent interdependence between the stiffness and strength of a steel MRF. Therefore, when a hybrid-steel-based MRF or a dual-steel-based MRF is subjected to a seismic event, the damage-control behaviour [11–14] that restricts inelastic damages in preselected members or locations can be guaranteed in a wide deformation range, which is very desirable for improving the seismic performance of steel MRFs.

The great potential of extending the hybrid-steel-based or the dual-steel-based concept to seismic resistant steel MRFs has been supported by recent works. For instance, Charney and Atlayan [5] developed the hybrid steel MRF constructed by members with different steel grades, and the sound seismic performance with reduced residual deformations of the system was validated by a numerical investigation. Dubina et al. [7] proposed that the rational utilisation of HSS in steel MRFs will facilitate the exploitation of plastic energy dissipation in beams without significant damages accumulated in columns or connections. More

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recently, Ke and Chen [14] proposed the concept of a dual-steel-based steel MRF, namely, high-strength steel MRF equipped with energy dissipation bays (HSSF-EDB). In particular, the system is composed of a main frame of HSS and sacrificial beams of mild carbon steel in the energy dissipation bays. Under earthquake loadings, the energy dissipation bays act as active dampers and provide plastic energy dissipation, while the HSS main frame can respond elastically in the expected deformation range. In this context, a damage-control stage will be formed in the nonlinear pushover curve of a HSSF-EDB structure. Later, Ke and Yam [15] proposed a direct-iterative design approach for conducting preliminary design of a HSSF-EDB system achieving damage-control behaviour under expected seismic excitations.

From the perspective of performance-based seismic engineering and seismic resilience enhancement, a methodology for prescribing the seismic demand of HSSF-EDBs in the damage-control stage where the HSS MRF generally stays elastic is a critical issue. In practical engineering, static evaluation procedures (e.g. nonlinear pushover analysis method), which enable designers to reasonably quantify the nonlinear seismic demand of a structure before it can be analysed with a more rigorous approach, i.e. the nonlinear response history analysis (NL-RHA), are generally preferred in the design procedure. In this respect, Ke et al. [16] recently developed the dual-energy-demand-index-based (DEB) procedure for quantifying the demand indices of low-to-medium-rise damage-control systems under expected earthquake ground motions. Specifically, based on single-degree-of-freedom (SDOF) systems with significant post-yielding stiffness ratio that can generally describe the nonlinear behaviour of a structure in the damage-control stage, the energy factors [15–20] deduced from the modified Housner principle [21] and the cumulative ductility [22–24] determined from the total dissipated plastic energy are used as the core demand indices to prescribe the seismic demand of a structure. As a typical evaluation procedure using multiple performance indices [25,26] for prescribing seismic demand, the DEB procedure prescribes the peak response demand and the cumulative response demand concurrently. Nevertheless, since only the fundamental vibration mode is considered in the DEB procedure, it is valid only for low-to-medium-rise structures. Therefore, for taller HSSF-EDBs which may show high sensitivity to higher vibration modes, the quantification of seismic demands characterising the damage-control behaviour is computationally consuming as the performance evaluation may be totally dependent on the NL-RHA.

The present work is a continuation of the DEB procedure and contributes towards a practical evaluation method for quantifying the seismic demands of multi-mode-sensitive HSSF-EDBs in the damage-control stage which have not been considered in the previous studies. Based on the multi-mode nonlinear pushover analysis and energy balance of equivalent modal SDOF systems representing the essential modes of a structure, a modified DEB procedure is developed, and the rationale of the modified DEB procedure is also clarified in detail. To demonstrate the procedure, the modified DEB procedure is applied to prototype HSSF-EDBs that are appreciably influenced by multi-modes, and the results determined by the modified DEB procedure are compared with those determined by the conventional DEB procedure and those from NL-RHA.

2. Development of the modified dual-energy-demand-index-based (DEB) procedure

2.1. Underlying assumptions

The modified DEB procedure is motivated by the energy balance of equivalent modal SDOF systems for characterising the response of a multi-mode-sensitive HSSF-EDB acting as a multi-degree-of-freedom (MDOF) system under earthquake ground motions. In particular, the underlying assumptions are listed as follows:

(1) The seismic energy balance of the entire structure as a MDOF system can be represented by the energy balance of the equivalent modal SDOF systems of essential modes, and the coupling effect among modal SDOF systems arising from the inelastic action of the structure is neglected.
(2) The superposition of the seismic responses of equivalent modal SDOF systems for characterising the behaviour of the entire MDOF system can be extended to inelastic stage for practical applications.
(3) The pushover response curve (skeleton response curve) of a HSSF-EDB can be approximated by a trilinear idealisation, and a bilinear kinematic model with significant post-yielding stiffness ratio can be utilised to describe the response curve of the system in the damage-control stage.

It is worth pointing out that although the utilisation of the first two assumptions compromises the theoretical rigorousness of preserving the computational simplicity of a static procedure, the rationale is in line with the widely used modal pushover analysis procedure [27], and the effectiveness of the two assumptions for practical applications is validated by extensive research works [28–30]. As for the third assumption, the viability has also been echoed by the test results extracted from the experimental programme of a large-scale HSSF-EDB [14,15]. The feasibility of using the multi-linear approximation for idealising the nonlinear pushover curve of a structure is supported by research findings from recent investigations [27–30] and documented in design specifications [31,32]. The accuracy of all these assumptions for quantifying the seismic demand of multi-mode-sensitive HSSF-EDBs in the damage-control stage will be further validated in the following sections.

2.2. Dual-energy-demand indices of equivalent modal SDOF systems

The fundamental performance requirements of HSSF-EDBs achieving the damage-control behaviour [16] are reproduced as follows: (1) The HSS MRF stays generally elastic under expected ground motions with damages locked in the energy dissipation bays equipped with sacrificial beams; (2) The sacrificial beams should provide a stable source of plastic energy dissipation to balance the accumulated plastic energy demand of earthquake ground motions. Thus, both the peak response demand and the cumulative response demand of a structure should be prescribed in seismic evaluations of the HSSF-EDBs.

A recent experimental investigation of a HSSF-EDB responding in the damage-control stage indicates that the nonlinear base shear versus displacement response can be idealised by a bilinear kinematic model with significant post-yielding stiffness ratio [15,16]. The good agreement between the test results and the idealised model curve is reproduced in Fig. 1a. Therefore, the bilinear kinematic hysteretic model with significant post-yielding stiffness ratio is assigned to the modal SDOF systems for developing the modified DEB procedure in this work. Accordingly, the seismic response of a tall HSSF-EDB can be simplified by the combination of the responses of equivalent modal SDOF systems representing essential modes. The energy factor (γ_n) of an equivalent modal SDOF system representing the "**n**th" mode is utilised to quantify the peak response demand considering the corresponding mode. As shown in Fig. 1b, the nominal absorbed energy defined by the covered area of the nonlinear base shear versus displacement curve of a SDOF system is calculated by the product of the energy factor and the absorbed energy of the corresponding elastic SDOF system assigned with the identical elastic properties (i.e. mass, stiffness and damping ratio) of the "**n**th" mode, and the energy balance equation for the SDOF system [15–17] is reproduced as follows:

$$\gamma_n E_{aen} = E_{an} \tag{1}$$

where E_{aen} = absorbed energy of the corresponding elastic SDOF