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Application of the hybrid force/displacement (HFD) seismic design method to composite steel/concrete plane frames

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ABSTRACT

This paper proposes a performance-based seismic design method for composite steel/concrete moment-resisting frames (MRFs) consisting of I steel beams and square concrete filled steel tube (CFT) columns. The design method has to do with the hybrid force/displacement (HFD) method, which combines the advantages of both the force-based and displacement-based seismic design procedures. This hybrid method incorporates predefined values of the maximum story drift and local ductility to a target roof displacement and then determines the appropriate behavior (strength reduction) factor for limiting the roof displacement ductility. The HFD method uses conventional elastic response spectrum analysis and takes into account the influence of structural parameters, such as the number of stories, beam-to-column stiffness and strength ratio as well as the material strength. Comparisons of the proposed design method with those adopted by current seismic design codes demonstrate that the proposed procedure appears to be more rational and efficient indicating the tendency of the current seismic design codes to overestimate the maximum roof displacement and underestimate the maximum inter-story drift ratio along the height of the frames. Furthermore, comparisons between CFT-MRFs and pure steel ones reveal that the first type seems to be more cost-effective structures than the latter since they are associated with a higher behavior factor implying a better seismic behavior of the former.

1. Introduction

Engineers have been studying for many years the effects of significant earthquakes on building structures and they have emphasized the fact that the seismic risk in urban areas is increasing and is associated with socio-economically unacceptable levels. In recent years, many efforts have been directed to: a) the conversion of existing seismic code provisions to more efficient ones or the development of more rational seismic design methods and b) a more successful design of new engineering structures as well as the seismic vulnerability assessment and strengthening of existing ones. Thus, design approach should not only consider conventional design aspects but also deal with damage control both in structural and non-structural elements.

The SEAOC Vision 2000 Committee in 1995 [1] has proposed the "Performance-Based Seismic Engineering of Buildings" (PBSE) report, also called "performance-based earthquake engineering" (PBEE), in which the above-mentioned developments have been incorporated. The conceptual framework for PBSE and also the various methodologies that have been developed for the application of such framework to the design of building structures named "performance-based seismic design" (PBSD) or simply "performance-based design" (PBD) are presented in this report. The emerging need to consider different criteria associated with various levels of performance has led to a recent emphasis on, and important developments in, PBD. The main objective of this new design philosophy is to achieve the desired behavior of the structure for different levels of seismic action [2,3].

To achieve the objectives of PBD of a structure one should determine levels of seismic activity (seismic hazard levels) and the respective desired levels of structural damage (damage level). Each pair of seismic design action and damage level is a separate "performance level", while the total of performance levels constitute the behavior–design goals "performance objective". The performance-based design is based on the idea that it is possible to associate the desired structural behavior with the damage of the building in terms of ductility (μ) and inter-story drift ratio (*IDR*). On the basis of this new design philosophy, three new seismic design codes were created: SEAOC [1], ATC 40 [4] and FEMA-273 [5]. These seismic codes provide different levels for the maximum allowable μ_θ and *IDR*, which are based on the structural system and material. However, rational and efficient design procedures are needed to provide realistic relationships that associate the given drift and ductility demands with the seismic strength requirements.

According to the force-based design (FBD) method (e.g., [6]), the designer uses two limit states, namely, the ultimate limit state (ULS)

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and the damage limit state (DLS), associated with the design seismic action (475 years return period) and the frequent seismic action (95 years return period), respectively. The avoidance of a premature collapse mechanism is ensured by using the capacity rule (capacity design). In accordance with the capacity design, main structural elements such as columns are designed to remain elastic, while the beams are allowed to develop plastic hinges. The strength-based design of a structure by using the FBD method should satisfy the ULS. This is achieved through the behavior factor q (or strength reduction factor R in U.S.) which is used to reduce the forces obtained from an elastic analysis or to reduce the ordinates of the elastic design spectrum. In this way the factor q controls indirectly the ductility capacity and the overstrength of the structure. Based on the reduced design forces the structure is designed for the ULS strength requirements. Then, the DLS drift-based design is checked. More specifically, the story drifts of the structure are limited at specific values that satisfy service requirements under frequent earthquakes. If the strength requirements of ULS or the story drift limits of DLS are not satisfied, the structure is re-designed for different cross-sections and for increased stiffness, respectively. The above procedure shows the FBD to be an iterative method since its requirements are based on a trial and error process depending on the designer's experience.

In recent years, there has been a great tendency toward performance-based seismic design of structures and alternative design methods have been developed. In this connection, the most well-known design methods are the capacity spectrum method [7], the N2 method [8], and the direct displacement-based design (DDBD) method proposed by Priestley [9] and described in detail in the book of Priestley et al. [10]. The DDBD method has been successfully applied to the seismic design of reinforced [11,12], steel [13,14] and composite steel/concrete frames [15].

Displacement-based and in general performance-based seismic design methods employ indirectly (through displacements) or directly the concept of damage, usually quantified with the aid of various damage indices [16–18]. These indices are expressed in terms of deformation, dissipated energy or a combination of deformation and dissipated energy. Among the works dealing with damage-based seismic design methods one can mention those of Kawashima and Aizawa [19], Park et al. [15], Ballio and Castiglioni [20], Tiwari and Gupta [21], Kunnath and Chai [22], Bozorgnia and Bertero [23], Panyakapo [24,25], Lu and Wei [26], and Ghobarah and Safar [27]. Hatzigeorgiou and Beskos [28] and Kamaris et al. [18] developed a new design method for plane concrete/masonry and for steel moment resisting framed structures, respectively, called direct damage-controlled design (DDCD).

Use of advanced finite element methods for static and dynamic inelastic structural analysis in performance-based design with different design criteria (drift, ductility, damage) has also been reported. One can mention here the works of Kappos and Manafpour [29] and Kappos and Panagopoulos [30] for the seismic design of reinforced concrete frames and Vasilopoulos and Beskos [31,32] for the seismic design of steel frames.

This paper presents a new preliminary PBSD methodology for composite plane moment-resisting frames (MRFs) consisting of I steel beams and concrete filled steel tube (CFT) columns. This methodology combines the advantages of the well-known force-based and displacement-based seismic design methods in a hybrid force/displacement (HFD) design scheme and works in a PBD framework. The method has been proposed in the preliminary work of Karavasilis et al. [33] and evolved by extensive parametric studies of the authors [34–38] to reach its final stage dealing with plane steel frames of various kinds [39]. Herein, the HFD method is extended to CFT-MRFs and applied to realistic design examples of CFT-MRFs using the formulae proposed by Skalomenos et al. [40] and those presented here, which are based on a more refined modeling than in Tzimas et al. [39]. Furthermore, comparisons with CFT-MRFs designed according to the FBD method are made on the basis of nonlinear time-history analyses of the designed frames under ten semi-artificial accelerograms for three performance levels. The results demonstrate the advantages of the proposed method over the force-based seismic design procedure of EC8 [6]. Finally, CFT-MRFs are designed on the basis of the HFD method using equations developed here according to the assumptions of the HFD of Tzimas et al. [39] in order to be compared on an equal basis with the pure steel frames considered in the study of Tzimas et al. [39]. The comparison results lead to useful conclusions concerning the seismic design and behavior of CFT-MRFs.

2. The HFD method

According to PBD philosophy, drift and ductility demands should be determined with sufficient accuracy during the seismic design of building structures. The socio-economic losses, the possible building demolition and human life protection are related to the drift and ductility that occurred in the buildings due to a seismic event. These deformations should be restricted to specific values to avoid significant damages on structural and non-structural elements and therefore, it would be very useful if they are directly associated with the behavior (strength reduction) factor for any limit state [34,40].

The HFD method proposes relationships for the behavior factor that correlates the seismic strength requirements with the design criteria in order to restrict maximum roof ductility to a predefined value. This is achieved by incorporating target values of the drift and local ductility to a target roof displacement and then by calculating appropriate behavior factor for limiting the roof displacement ductility. According to the HFD method (a) the input variables for the initiation of the design process are both drift and ductility demands; (b) the use of a substitute single-degree-of-freedom (SDOF) as recommended by the DDBD method is avoided; (c) the conventional elastic response spectrum is used in the analysis; and (d) the influence of structural parameters, such as the number of stories, the beam-to-column stiffness and strength ratio and the material strengths are included.

In the following paragraphs, the procedural steps of the method are presented. These steps are based on those described in Tzimas et al. [39] for the case of steel frames, appropriately modified and extended to the present case of composite steel/concrete frames. Thus, the proposed hybrid force/displacement (HFD) seismic design procedure can be summarized in the following steps:

(1) Definition of the basic building attributes
Definition of the number of stories, n_s, number of bays, n_b, bay widths and story heights is provided and limits on the depth of beams and columns due to architectural requirements, are imposed.

(2) Definition of the performance level
The performance levels considered here are the immediate occupancy (IO) under the frequently occurred earthquake (FOE), the life safety (LS) under the design basis earthquake (DBE) and the collapse prevention (CP) under the maximum considered earthquake (MCE). The earthquake intensity level is represented by the appropriate elastic acceleration response spectrum, for each performance level. Fig. 1 shows three elastic displacement and pseudo-acceleration design spectra, which indicate the three seismic design actions for the three aforementioned performance levels. These spectra were defined based on the design response spectrum of EC8 [6], for soil class B, peak ground acceleration of the earthquake design equal to 0.35 g and 5% damping.

(3) Definition of input parameters (performance metrics)
Definition of limit values for the maximum inter-story drift ratio (IDR_{max}) and maximum local ductility (member rotation ductility, μ_θ, for beams/columns) along the height of the frame. These limit values are selected based on the performance level defined by FEMA273 [5] or SEAOC [2].