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Seismic damage estimation of in-plane regular steel/concrete composite moment resisting frames

George S. Kamaris [a], Konstantinos A. Skalomenos [b], George D. Hatzigeorgiou [c,*], Dimitri E. Beskos [d,e]

[a] School of Engineering, University of Warwick, Coventry CV4 7AL, United Kingdom
[b] Disaster Prevention Research Institute (DPRI), Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[c] School of Science and Technology, Hellenic Open University, GR-26335 Patras, Greece
[d] Department of Civil Engineering, University of Patras, GR-26500 Patras, Greece
[e] Office of Theoretical and Applied Mechanics, Academy of Athens, 4 Soranou Efessiou, GR-11527 Athens, Greece

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ABSTRACT

Simple empirical expressions to estimate maximum seismic damage on the basis of four well known damage indices for planar regular steel/concrete composite moment resisting frames having steel I beams and concrete filled steel tube (CFT) columns are presented. These expressions are based on the results of an extensive parametric study concerning the inelastic response of a large number of frames to a large number of ordinary far-field type ground motions. Thousands of nonlinear dynamic analyses are performed by scaling the seismic records to different intensities in order to drive the structures to different levels of inelastic deformation. The statistical analysis of the created response databank indicates that the number of stories, beam strength ratio, material strength and ground motion characteristics strongly influence structural damage. Nonlinear regression analysis is employed in order to derive simple formulae, which reflect the influence of the aforementioned parameters and offer a direct estimation of the damage indices used in this study. More specifically, given the characteristics of the structure and the ground motion, one can calculate the maximum damage observed in column bases and beams. Finally, three examples serve to illustrate the use of the proposed expressions and demonstrate their accuracy and efficiency.

1. Introduction

Damage in a structure under loading can be defined as the degradation or deterioration of its integrity resulting in reduction of its load capacity. In earthquake-resistant design of structures, some degree of damage in the structural members is generally accepted. This is done because the cost of a structure designed to remain elastic during a severe earthquake would be very large. Thus, existing seismic codes, e.g., EC8 [1], in an implicit way and more recent performance-based seismic design methods [2–4] in an explicit and more systematic way employ the concept of damage to establish structural performance levels corresponding to increasing levels of earthquake actions. These performance levels mainly describe the damage of a structure through damage indices, such as the inter-story drift ratio (IDR), or the member plastic rotations.

Several methods to determine damage indices as functions of certain response parameters have been presented in the literature. In general, these methods can be noncumulative or cumulative in nature. The most commonly used parameter of the first class is ductility, which relates damage only to the maximum deformation and is still regarded as a critical design parameter by codes. To account for the effects of cyclic loading, simple rules of stiffness and strength degradation have been included in various noncumulative indices [5–7], mainly referred to reinforced concrete members. Cumulative-type indices can be divided in deformation based [8] or hysteresis based [9,10] formulations and methods that consider the effective distribution of inelastic cycles and generalize the linear law of low-cycle fatigue of metals through a hypothesis of linear damage accumulation [11]. Sucuoğlu and Erberik [12] developed low-cycle fatigue damage models for deteriorating systems on the basis of test data and analysis and Kamaris et al. [13] proposed a new damage model exhibiting strength and stiffness degradation which takes into account the phenomenon of low-cycle fatigue and the interaction between axial force and bending moment at a section of a beam-column steel member. Combinations of deformation and energy dissipation have been also proposed to establish damage indices [14]. In these methods damage is expressed as a linear combination of the damage caused

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* Corresponding author. Tel.: +30 2610 367769.
E-mail address: hatzigeorgiou@eap.gr (G.D. Hatzigeorgiou).

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by excessive deformation and that due to repeated cyclic loading effects [14]. An extensive review of damage indices used in the literature can be found in Powell and Allahabadi [15]. Finally, the concept of continuum damage mechanics [16] in conjunction with the finite element method of concentrated inelasticity has been employed in the analysis of steel and reinforced concrete structures [17,18] for the determination of their damage.

The composite moment resisting frames (MRFs) having concrete-filled steel tube (CFT) columns and steel girders (CFT-MRFs) (Fig. 1) are a relatively new type of structures which offers significant advantages for use as the primary resistance systems in building structures subjected to seismic loading. The CFT-MRF systems exhibit desirable features, such as large energy dissipation and increased strength and stiffness to control the drifts. For these reasons, they have increasingly investigated during the last decades for understanding their behavior under seismic loads [19–21] and have been popular in mid-rise and high-rise buildings in Japan and the U.S.

The main objective of this paper is to study the seismic inelastic behavior of CFT-MRFs and quantify their damage through simple expressions that relate the most commonly used damage indices of the literature with the characteristics of the frames and the ground motions. Similar expressions have been proposed by the authors for steel MRFs and X-braced frames [22], but research on CFT-MRFs is still missing. For that reason, a large number of CFT-MRFs are subjected to an ensemble of 100 ordinary (i.e. without near-fault effects) ground motions scaled to different intensities. A response databank is created and a regression analysis is performed in order to derive simple formulae that can be used for the prediction of damage. Three examples are utilized to illustrate the use of the proposed formulae and demonstrate their efficiency and accuracy. It should be pointed out that the seismic damage calculated herein is "probably expected" and not a deterministic damage value, since the procedures utilized in this paper are based on statistical formulae.

The proposed methodology provides the means of a rapid and accurate damage assessment of existing structures, avoiding the use of the more sophisticated and time consuming non-linear dynamic analysis. It can also be utilized in the preliminary design of structures in the framework of a performance based design approach in order to size a frame to achieve a preselected damage level. Thus, the designer can perform a high quality preliminary design based on elastic analysis and the proposed relationships, which can significantly decrease the need for iterations in an analysis/design procedure. This is very important when analysis is non-linear dynamic and time consuming. Finally, the main advantages of the proposed formulae are simplicity, accuracy and rapid damage estimation, which is usually done by advanced and costly methods of analysis.

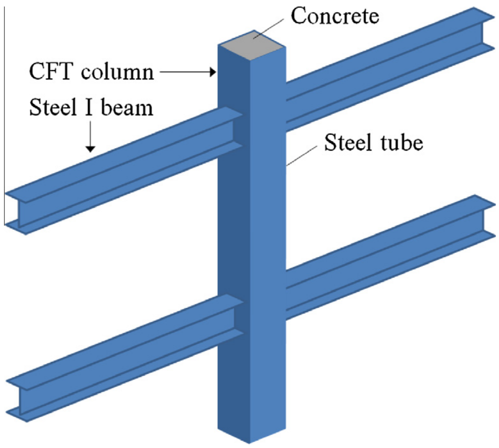

Fig. 1. CFT-MRF configuration.

2. Damage indices used in this study

The proposed damage expressions are associated with four damage indices existing in the literature. These are the damage indices of Park and Ang [14], Bracci et al. [10], Roufaiel and Meyer [6] and Banon and Veneziano [5]. These indices have been selected here because (i) they are the most widely used in applications and (ii) they can be easily employed with the aid of the Ruaumoko 2D program [23]. In the following, a brief description of all these four damage indices will be given for reasons of completeness.

The damage index D_{PA} of Park and Ang [14]is expressed as a linear combination of the damage caused by excessive deformation and that contributed by repeated cyclic loading effects, as shown in the following equation:

$$D_{PA} = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE \tag{1}$$

In the above, the first part of the index is expressed as the ratio of the maximum experienced deformation δ_m to the ultimate deformation δ_u under monotonic loading. The second part is defined as the ratio of the dissipated energy $\int dE$ to the term $(Q_y\delta_u)/\beta$, where Q_y is the yield strength and the coefficient β is a non-negative parameter determined from experimental calibration. In this work, β is taken equal to 0.025 for the steel beams [24] and 0.03 for the CFT columns [25] of the frames used herein.

Bracci et al. [10] suggested a damage index equal to the ratio of 'damage consumption' (loss in damage capacity) to 'damage potential' (capacity), defined as appropriate areas under the monotonic and the low-cycle fatigue envelopes. Thus, the 'damage potential' D_P is defined as the total area between the monotonic load–deformation curve and the fatigue failure envelope. As damage proceeds, the load–deformation curve degrades, resulting in the damage D_s due to the loss of strength, while the irrecoverable deformation causes the deformation damage D_D. Thus, this damage index D_{BRM} is expressed as

$$D_{BRM} = \frac{D_D + D_S}{D_P} \tag{2}$$

Roufaiel and Meyer [6] proposed that the ratio between the secant stiffness at the onset of failure M_m/ϕ_m and the minimum secant stiffness reached so far M_x/ϕ_x, can be used as a good indicator of damage. Based on that, they defined the modified flexural damage ratio (MFDR) or D_{RM} as

$$D_{RM} = \mathrm{MFDR} = \max[\mathrm{MFDR}^+, \mathrm{MFDR}^-] \tag{3}$$

$$\mathrm{MFDR}^+ = \frac{\phi_x^+}{M_x^+} - \frac{\phi_y^+}{M_y^+} \Bigg/ \frac{\phi_m^+}{M_m^+} - \frac{\phi_y^+}{M_y^+},$$
$$\mathrm{MFDR}^- = \frac{\phi_x^-}{M_x^-} - \frac{\phi_y^-}{M_y^-} \Bigg/ \frac{\phi_m^-}{M_m^-} - \frac{\phi_y^-}{M_y^-} \tag{4}$$

where ϕ is the beam curvature due to a bending moment M, the term M_y/ϕ_y is the initial elastic stiffness and subscripts + and − denote the loading direction.

The Banon and Veneziano [5] analysis is set in a probabilistic context and their model has been calibrated on the basis of 29 different tests on reinforced concrete elements and structures, selected from among the most representative ones in the technical literature. In particular, the damage parameters d_1 and d_2 are defined, respectively, as the ratio of stiffness at yielding point to secant stiffness at failure, and the plastic dissipated energy E_h