Soil Dynamics and Earthquake Engineering 109 (2018) 266–272

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Consistent damage model and performance-based assessment of structural members of different materials

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ARTICLE INFO

Keywords:
Members of different materials
Consistent damage model
Combination coefficient
Performance levels
Normalizing parameter

ABSTRACT

Structural members of different materials in composite structures have different seismic damage performances. Consequently, a unified standard is required to evaluate the performance levels of structural members of a composite structure in order to determine the behavior and the damage process from member-level to structure-level. Based on the classical Park-Ang damage model, a consistent modification of that model is proposed for structural members of different materials. Furthermore, the specific limit values of this damage model at various performance levels are calculated. Obvious differences have been found between the limit values of different types of members. In order to unify the damage limits that correspond to predefined performance levels such that a comparison between different members can be made directly, normalizing parameters for the different types of members are introduced to build the unified damage model. The finite element method utilizing the proposed damage model and performance levels produces results in good agreement with those of testing.

1. Introduction

With recent advances in structural materials and construction methods, various composite structural systems consisting of two or more structural members of different materials have been developed and used in building construction [1]. For example, the reinforced concrete (RC) core tube-steel frame structure involves the use of a RC shear wall system to provide the lateral resistance to the earthquake ground motion and a steel frame system to resist the gravity forces. Another typical example is the vertically mixed concrete-steel structure, which is usually composed of a RC substructure and a steel superstructure. Its lateral stiffness changes along its height to generate smaller structural deformation.

Composite structural systems combine the advantages of different materials and different members to improve the structural performance. In composite structures, the damage performance and failure mechanisms of different members are quite different, as shown in Fig. 1, which displays the typical load-displacement curves of a RC column [2], a steel column [3] and a concrete encased steel (CES) column [4]. Hence, to accurately evaluate the performance of composite structures, it is essential to develop a suitable model for the damage assessment of structural members made of different materials.

Damage models have been proposed to quantitatively define and evaluate the seismic damage of members and structures, thus making seismic design more controllable under different structural or non-structural needs [5]. However, most of the existing damage models are proposed for structural members of a specific material, not for members of different materials. For example, the widely used Park-Ang [6] damage model was initially proposed for RC members and its application to steel members and steel-concrete composite members has not been fully validated. In addition, the nonlinearity of structural behavior makes it difficult to progress from damage prediction at member-level to that at structure-level, especially for composite structures. A weighted damage indicator was proposed by Park et al. [7] to represent the damage behavior from member-level to structure-level for RC buildings. Yet, because damage mechanisms and corresponding performance levels for members of different materials are obviously different, prediction of the behavior and the damage process from member-level to structure-level for composite structures is difficult.

To clarify the seismic performance of composite structures, one has to take into account the variations of the energy dissipation and the damage or failure mechanisms of members of different materials. In this paper, a unified modification of the Park-Ang [6] damage model and corresponding performance levels are developed, which are suitable for structural members of different materials. Then, normalized parameters are introduced to the damage model to specify the damage limits at

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https://doi.org/10.1016/j.soildyn.2018.03.021
Received 16 March 2018; Accepted 19 March 2018

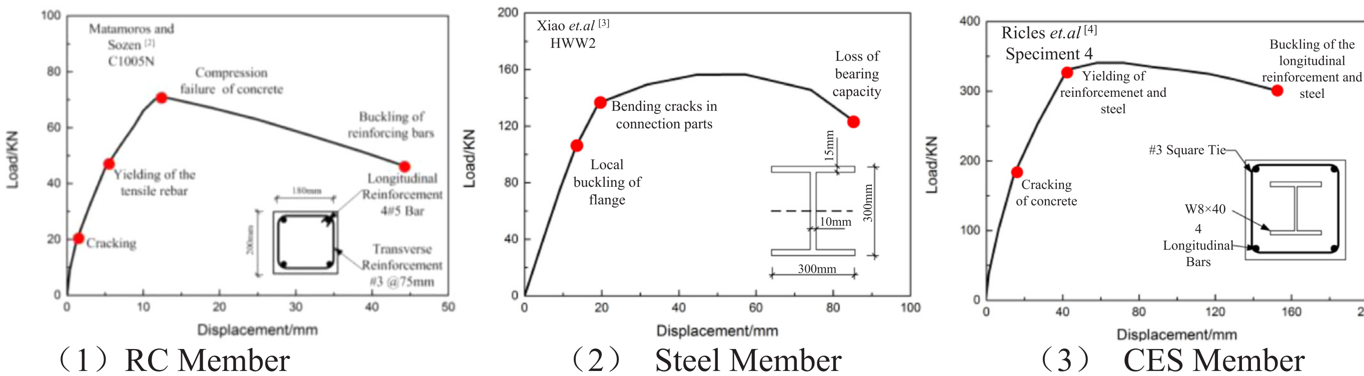

Fig. 1. The load-displacement curve of different material column.

Table 1
The damage index of Park-Ang model and the observed damage [6].

Damage index	Damage degree	Physical appearance
$D < 0.1$	Slight	Sporadic occurrence of cracking;
$0.1 \le D < 0.25$	Minor	Minor cracks throughout building. Partial crashing of concrete in columns;
$0.25 \le D < 0.4$	Moderate	Extensive large cracks. Spalling of concrete in weaker elements;
$0.4 \le D < 1.0$	Severe	Extensive crashing of concrete. Disclosure of buckled reinforcements;
$D \ge 1.0$	Collapse	Total or partial collapse of building.

each performance level for different members, in order to connect the generalized damage model and the damage performance of these members and understand the damage behavior from member-level to structure-level for composite structures. Finally, the proposed damage model is used to study damage and performance evolution in a 12-storey RC-CES-Steel vertically mixed frame structure.

2. The Park-Ang damage model

Defined as a linear combination of damage induced by ultimate deformation and cumulative dissipated energy, the Park-Ang [6] damage model is one of the best known and most widely used damage model. It expresses the damage index D by the relation

$$D = \frac{\delta_m}{\delta_u} + \beta_{PA}\frac{\int dE}{F_y\delta_u} \tag{1}$$

where δ_u is the ultimate displacement under monotonic loads, δ_m is the maximum displacement under loading, F_y is the yield strength, dE is the incremental absorbed plastic hysteretic energy, and β_{PA} is a combination coefficient as proposed by Park and Ang [6]. The values of the damage index D in case of different damage states are shown in Table 1.

This model, even though it has been applied to many practical damage evaluation problems of RC structures and incorporated in the well-known non-linear reinforced concrete damage analysis program IDARC [8], still, it cannot exactly evaluate the damage of structures made of other than reinforced concrete materials.

3. Consistent damage model

In order to appropriately describe the evaluation of damage states of composite structures, a damage index should satisfy the following conditions [5]: 1) be a monotonically increasing function; 2) be dimensionless and attain values between 0 for an undamaged (elastic) state and 1 for a failure or collapsed state of the structure. In order to satisfy the above conditions and be applicable to structural members with different materials, a modified Park-Ang damage model, the so called consistent damage model, is developed here in the form

$$D_i = (1-\beta_i)\frac{\delta_m - \delta_y}{\delta_u - \delta_y} + \beta_i\frac{\int dE}{F_y(\delta_u - \delta_y)} \tag{2}$$

where the parameter β_i is the combination coefficient for material i, such as the material of RC members, steel members or CES members. In this model, the structural member is considered as non-damaged before its yielding. Thus, the maximum deformation δ_m under loading is determined as

$$\delta_m = \begin{cases} \delta_y, & \delta_m \le \delta_y \\ \delta_m, & \delta_m > \delta_y \end{cases} \tag{3}$$

Where δ_y is the deformation at yielding.

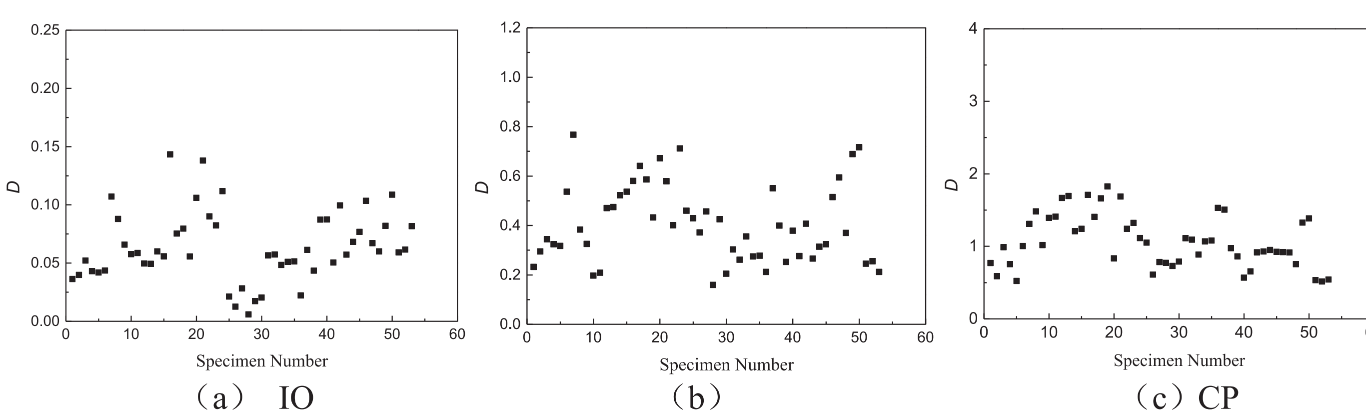

Fig. 2. The damage index of RC member at three performance levels.