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Fragility relationships for torsionally-imbalanced buildings using three-dimensional damage characterization

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Abstract

In this paper, a methodology for the derivation of fragility relationships for three-dimensional (3D) structures with plan irregularities is developed. To illustrate the procedure, fragility curves are derived for an irregular reinforced concrete (RC) building under bi-directional earthquake loadings. In order to represent the damage state of irregular structures, a spatial (3D) damage index is employed as the salient response parameter. The feasibility of using a lognormal distribution for the bounded response variables, as in the case of structural fragility analysis, is investigated. Through the comparison between the fragility curves derived using the spatial and the previously-existing damage indices, it is shown that the proposed method provides realistic results and is therefore recommended for fragility analysis of buildings with significant torsional and bi-directional responses.

Keywords: Fragility curves; Earthquake response; Irregularity; Torsion; Bi-directional; Damage index

1. Introduction

Fragility curves, used for the assessment of seismic losses, are in increasing demand, both for pre-earthquake disaster planning and post-earthquake recovery and retrofitting programs. This is due to the difficulties associated with analyzing individual structures and the importance of obtaining a global view of anticipated damage or effects of intervention, before and after an earthquake, respectively. Analytically-derived, mechanics-based fragility relationships result in reduced bias and increased reliability of assessments compared to the fragilities based on post-earthquake observations [1] or on expert opinion (e.g. HAZUS [2]). Since analytical methods are based on statistical damage measures from analyses of structural models under increasing earthquake loads, employing an appropriate damage assessment method is central to deriving fragility curves.

For the seismic assessment of structures with planar irregularities, a damage measure should be able to reflect 3D structural response features such as torsion and bi-directional response. In this study, a 3D damage characterization is utilized to represent the damage states of buildings with plan irregularities. The latter method accounts for the multi-directionality of earthquake motions as well as the asymmetry of the structure. It therefore captures the true three-dimensional inelastic effects that govern the response of structures. The adoption of such a damage measure opens the door to the derivation of spatial fragility relationships of irregular structures which have 3D responses, bi-directional deformation and torsion. In deriving fragility curves with the proposed damage measure, the validity of the statistical manipulation methods is carefully investigated. A systematic methodology to exclude unrealistic analyses results from the statistical treatment of response variables is proposed, and the feasibility of using lognormal distributions for bounded response variables, such as in the case of fragility derivation, is investigated.

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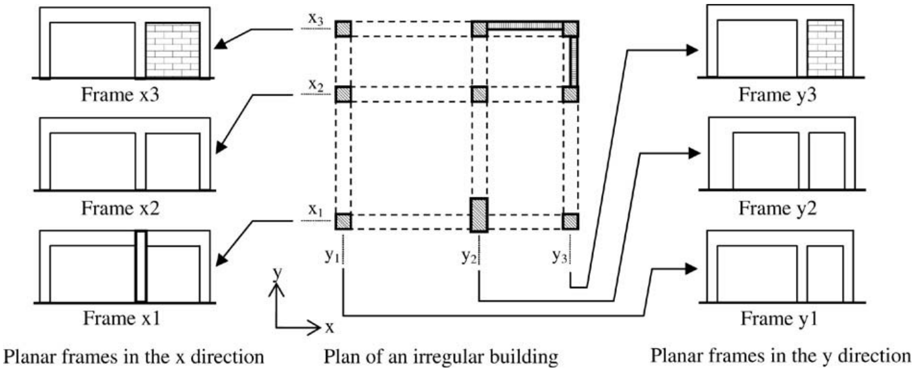

Fig. 1. Plan of an irregular building and frames used in planar decomposition.

2. Damage assessment method for spatially-responding buildings

The seismic assessment of buildings with irregular plans requires special attention, while regular structures can be readily idealized and assessed using the conventional 2D damage measures. Plan irregularities cause non-uniform damage levels among the members within a story and thus story-level damage indicators are inadequate in such cases. For instance, interstory drift cannot capture the localized variation in demand because the drift of columns varies according to their positions in their plane, due to torsion. In order to overcome the limitations of conventional damage measures, a 3D damage assessment method for torsionally imbalanced buildings is proposed, as described in subsequent sections of this paper.

2.1. Planar decomposition and local damage measure

To account for the torsional effects, a 3D structure is decomposed into planar frames that are considered to be the basic elements of lateral resistance, as shown in Fig. 1. Planar decomposition (Fig. 1) is not a method that physically separates structural components, but rather an approach that conceptually limits the response monitoring scope to a basic component (planar frame) in an integrated 3D structure. Therefore, while the geometry of a planar frame is defined in 2D, the response of the frame is not constrained to two-dimensional space. A planar frame may respond out-of-plane and be subjected to forces from other members orthogonally connected to it. Thus, the damage measure for planar frames (local damage measure) should be sensitive to these out-of-plane responses.

The comparison of the response of an RC column under unidirectional and bi-directional static loading is depicted in Fig. 2. Curves A and B are obtained from pushover analyses on the RC column subjected to unidirectional and bi-directional loadings, respectively. It is shown that the out-of-plane response (Curve B: bi-directional loading) leads to a strength reduction compared to the in-plane response (Curve A: unidirectional loading). Since the backbone envelope curve is obtained by a 2D pushover analysis, the differences from the latter curve mean that there exist additional damage-inducing factors other than in-plane monotonic deformation, which is the only source of damage featured in Curve A or the backbone curve. Thus the strength reduction below the latter curve can be a measure of additional damage due to the out-of-plane response (bi-directional loading). In cases of cyclic loading, strength reduction may also be caused by the effect of load reversals. Therefore, at a given deformation value, the strength reduction from the backbone envelope curve reflects the combined effects of out-of-plane actions and cyclic loading.

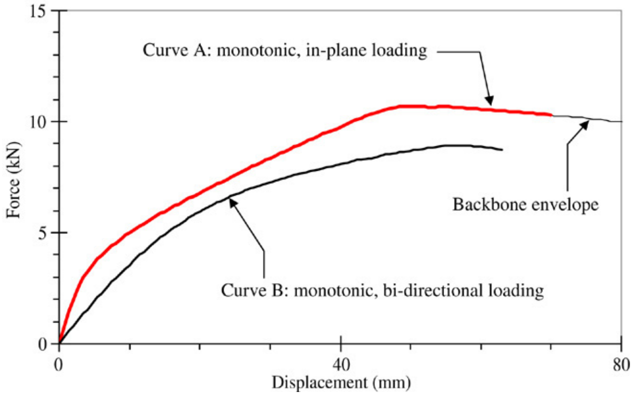

Fig. 2. Comparison of responses with and without out-of-plane loadings.

Based on the above discussion, the damage level (D) of a planar frame is defined as a combination of the damage due to in-plane monotonic displacement and the strength reduction from the backbone envelope curve, as given in Eq. (1).

$$D = \begin{cases} \dfrac{\Delta_p}{\Delta_u} + \left(1 - \dfrac{\Delta_p}{\Delta_u}\right) \cdot \dfrac{F_0 - F_p}{F_0 - F_f} & \text{for } \Delta_p \le \Delta_u \\ \dfrac{\Delta_p}{\Delta_u} & \text{for } \Delta_p > \Delta_u. \end{cases} \tag{1}$$

The parameters used in Eq. (1) are explained in Fig. 3, where a typical force–displacement relationship of an RC frame under bi-directional loading and its backbone envelope curve are presented. Δ_p and Δ_u are the displacement at peak response and the ultimate displacement, respectively. The peak response point (Δ_p) is not necessarily the maximum displacement. Instead, the damage level (D) needs to be monitored at several candidate peak response points (Δ_p) that may lead to the maximum damage level. Since the maximum value of D represents the maximum damage level of a planar frame during its response history, it is defined as the damage index (D_i) of the planar frame i.