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Energy-based sidesway collapse fragilities for ductile structural frames under earthquake loadings

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ABSTRACT

In assessing the likelihood of structural collapse under strong earthquake motions, uncertainties in structural properties and ground motions can be incorporated by use of a probabilistic analysis framework in conjunction with analysis methods such as incremental dynamic analysis (IDA). Maximum inter-story drift ratio (*IDR*) is typically selected as the key descriptor to characterize the global behavior of structural system in such a probabilistic assessment. The structural collapse capacity is often defined in terms of a threshold value of *IDR* or a reduced slope of the IDA curve between a selected seismic intensity measure and the corresponding *IDR*. However, collapse assessment approaches based on *IDR* may not accurately represent the overall structural collapse behavior due to redistribution and variation of local damage within the structure. Moreover, results of collapse predictions are found to be sensitive to variability in such drift measures, and assumed threshold values used in the collapse criterion. Recently, an energy-based seismic collapse criterion has been developed to describe collapse in terms of dynamic instability of the whole structural system caused by gravity loads. Using the energy-based collapse criterion, this paper proposes a more effective sidesway collapse risk assessment approach of ductile planar frames subjected to horizontal seismic loadings based on a new key descriptor of structural performance. The key descriptor, designated as the equivalent-velocity ratio, is related to the ratio of the energy dissipated through structural degradation to the seismic input energy. Using the equivalent-velocity ratio, a probabilistic collapse assessment method is developed for systematic treatment of uncertainties in the ground motions.

1. Introduction

Collapse prevention is one of the important design objectives of modern seismic provisions that ensures an acceptably small likelihood of structural collapse under the maximum earthquake loads considered in the design. Accurate and reliable assessment of collapse likelihood of structures requires probabilistic evaluation of structural collapse considering significant variability in applied ground motions and the chaotic nature of the dynamic behavior of a structure. Therefore, current seismic approaches for evaluating the response of structures are moving towards adopting a probabilistic assessment framework together with using analysis approaches such as incremental dynamic analysis (IDA), especially for the collapse risk of structures [1–6].

IDA is currently the most commonly used approach to evaluate the collapse performance of a structural system under earthquake excitations. This approach is based on the behavior of "IDA curves," which track the relationship between an "intensity measure" (IM) and a "damage measure" (DM) or "engineering decision parameter" (EDP) through nonlinear dynamic analyses under several ground motions scaled at incrementally increased intensity levels. The main premise of this approach is that IDA curves usually increase and then reach a plateau as an indication of collapse (i.e., exhibiting a large increase in the structural response for a small increase in the ground motion intensity). Sometimes IDA curves may show an erratic behavior instead of monotonically exhibiting an increase in the peak magnitude of the DM or EDP for a given increase in the IM. This phenomenon can make the process of collapse identification ambiguous or inaccurate. Common collapse criteria used in conjunction with IDA curves are: (1) "IM-based" criterion: showing a significantly reduced slope of the IDA curve, e.g. 20% of the initial slope; and (2) "DM-based" criterion: a large maximum inter-story drift ratio (*IDR*) exceeding an assumed global drift capacity, e.g., 10% [1]. There are also other approaches for

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DM-based criterion developed based on a combination that associates the *IDR* and the story shear force to identify sidesway collapse of frame structures [7,8]. However, it is noted that assessment results based on these collapse criteria may be sensitive to the assumed threshold values. Also, existing approaches that use maximum (peak) response of the structure such as *IDR* may not represent dynamic instability of the structural system necessarily [9,10].

Collapse fragility relation is a key outcome of a probabilistic assessment framework that quantities the collapse potential of structures. Collapse fragility curves show the conditional probability of collapse at a given seismic hazard level by identifying the likelihood of the "seismic demand" exceeding the "seismic capacity." Researchers have derived collapse fragility curves by statistical analysis of the collapse and non-collapse points on the IDA curves identified by the aforementioned collapse criteria [1,3,11,12]. The probability of the global collapse event of a structural system for a given intensity level is often estimated by the ratio of number of simulations resulting in collapse, i.e., seismic demand exceeding the seismic capacity, at a given intensity level to the total number of simulations performed at the same intensity level. Several other probabilistic regression approaches based on IDA curves have been introduced in the literature to quantify the uncertain structural capacity and conditional distribution of structural demand at a given intensity [12–16].

As investigated and confirmed by various approaches using IDA curves, there exists significant dispersion in probabilistic predictions of structural collapse. According to Krawinkler et al. [17], dispersion observed in collapse predictions can be addressed by selecting a larger set of ground motions in a way that variability in their characteristics and influences on collapse phenomenon are investigated properly. A search for alternative performance measures has therefore been initiated to assess collapse capacity of structures [16,18–26]. This literature highlights that peak story responses such as *IDR* may not completely represent the patterns and histories of significant structural damage observed before collapse. For a threshold level of *IDR* predetermined to identify collapse, distribution of damage through the structure shows significant variability, which may result in different damage states within the structural system rather than collapse, e.g., light, moderate, severe damage.

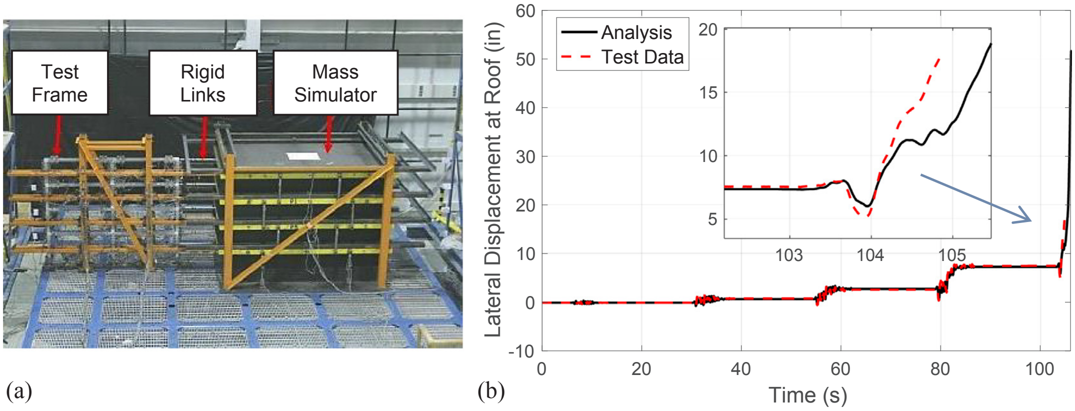
To address these challenges, characterization of the overall cumulative, i.e., load-path dependent, collapse performance of structures considering uncertainties is needed for efficient, accurate and reliable collapse risk assessment. Since energy parameters defined at a system-level are aggregated quantities considering the redistribution and variation of damage at each individual component within the structural system, they are potentially excellent indicators to represent the total structural damage history leading to collapse due to cyclic loading. Using energy-balance within structural systems, this paper focuses on developing a new procedure for the probabilistic collapse assessment of ductile planar structural frames under horizontal ground motions. Using three case studies of collapse experiments reported in the literature that involve sidesway collapse modes of steel structures [27–29], computational simulation models are developed and validated near collapse [9,10]. First, the energy-based collapse criterion, developed to describe the collapse based on dynamic instability due to gravity loads applied to the structure, is reviewed [9]. Next, using one of the test case studies [29], an effective performance descriptor representative of global structural collapse behavior is identified based on the energy-based criterion. The new descriptor, named as equivalent-velocity-ratio, describes the seismic demand and capacity of structural collapse based on the ratio of the degrading energy of the system to the seismic input energy. Using the energy-based collapse criterion and the new equivalent-velocity-ratio descriptor, a new procedure to derive collapse fragility relation is then presented for systematic treatment of uncertainties in ground motions using IDA curves.

In the following sections, a summary of the study is presented, while giving more details on the development of new energy-based probabilistic approaches in structural collapse assessment. To this end, the details of the computational simulation model for only one of the selected case studies [29] is provided in the next section to illustrate the framework of the study summarized above.

2. A four-story sidesway-collapse case study

Three experiments of steel moment resisting frames were investigated to identify the new energy-based criterion [9,10,30]. For these case studies, computational models were built using OpenSees [9,30,31] and validated by the experiment results. In the development of the computational models, macro-models that produce results consistent with the experiments were used. In these models, the softening response due to fracture or cyclic deterioration is addressed primarily through the use of a nonlinear moment-rotation response at the connections of the steel girders and columns. These models are efficient, less sensitive to numerical convergence issues, and detailed enough to simulate collapse behavior with a tolerated amount of additional dispersion in the evaluation of collapse strengths [28,29,32–34]. Of the three studies, the collapse experiment by Lignos et al. [29] is presented in this paper. Further details of this work and the other studies are available in Deniz [30].

The study by Lignos et al. [29] includes a series of collapse shake-table tests of a 4-story, 2-bay steel frame with reduced-beam sections (RBS) used in the girders, conducted at 1/8 scale. Fig. 1a shows the setup of the test frame on the NEES mass simulator at the University at Buffalo. The mass simulator is connected to the test frame by means of axially rigid horizontal links through which the simulator transfers P-



(a) (b)

Fig. 1. (a) Shake-table test from Lignos et al. [29,35], and (b) comparison between experimental test results and simulation results of lateral displacement time history at the top of the frame (1 in ≈ 2.54 cm).