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# Energy-based seismic collapse criterion for ductile planar structural frames

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ABSTRACT

One of the most common approaches to assess the collapse capacity of structures under earthquakes is incremental dynamic analysis (IDA), which tracks relationship between a structural damage measure and a ground motion intensity measure by so-called IDA curves. This IDA approach often uses collapse criteria given in terms of a large value of the maximum inter-story drift ratio, plastic hinge formations at structural components, or flattening of the IDA curve. However, these collapse criteria may not accurately represent the overall collapse behavior of structural systems due to redistribution and variation of damage within the structure. Moreover, collapse predictions by these subjective collapse limit-states are found to be sensitive to the assumed threshold values and to the characteristics of IDA curves. For more accurate assessment of collapse capacity and the likelihood of the collapse, this paper proposes a new collapse criterion that describes dynamic instability of frame structures in terms of the balance between the energies from the applied gravity loads and input ground motions. The collapse criterion is developed for planar frames under horizontally applied earthquakes and then tested using computational models of collapse behavior of ductile steel frame structures, which are validated by experiments reported in the literature. The collapse prediction results by the developed collapse criterion and existing criteria are compared in order to investigate sensitivity of the prediction results with respect to threshold values used by existing approaches. The results show that the proposed energy-based seismic collapse criterion is a more reliable option for assessing structural collapse of planar frames. The energy-based criterion can represent global dynamic instability of structural system more effectively by using aggregated quantities of energy responses of structural components instead of using assumed threshold values for structural responses such as story drifts.

## 1. Introduction

Modern seismic design provisions help enhance life safety of building occupants during a strong earthquake-shaking event by ensuring acceptably small probability of structural collapse. Accurate estimation of collapse likelihood of buildings under seismic excitations has recently become critical in efforts to promote hazard-resilience of the society, especially in developing national building codes, regional emergency response plans, and risk management strategies. Despite extensive research conducted in recent years, current collapse limit-states adopted in literature do not necessarily represent actual collapse at global scale but instead often focus on local damage at so-called near collapse or collapse prevention states.

Global collapse capacity of a frame structure under seismic excitation can be defined as the structural resistance just before the structure shows *dynamic instability*, that is, the structure, or any significant part of it, is not able to find a new equilibrium configuration, therefore loses the ability to sustain the gravity loads. A building structure is considered dynamically unstable when the structural system starts to show boundless story drifts. One of the most common approaches to determine the global collapse capacity of a structural system under earthquake excitations is incremental dynamic analysis (IDA) [1,2]. This approach constructs so-called "IDA curves" to identify relationship between an intensity measure (IM) (e.g., spectral acceleration of an earthquake input) and a damage measure (DM) or engineering decision parameter (EDP) (e.g., maximum inter-story drift ratio) through

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nonlinear dynamic analyses under ground motions at incrementally increased intensity levels. Since a dynamically unstable system exhibits a large increase in the structural response for a small increase in the ground motion intensity, the IDA curve becomes flattened, which indicates the collapse of the structural system. However, the flattening of IDA curves may not be clear or curves may show unusual behavior, such as non-monotonic behavior and discontinuities. To identify the collapse state despite such challenges, some collapse criteria have been proposed by Vamvatsikos and Cornell [1]: The building's global drift capacity against collapse was defined as the maximum story drift ratio at which the slope of the IDA curve reduces to 20% of the initial slope (''IM-based'' criterion), but if IDA curve does not fulfill the IM-based criterion, then one checks if the drift ratio exceeds an assumed global drift capacity, e.g., 10% (''DM-based'' criterion).

Although this approach is one of the state-of-art procedures in structural collapse capacity assessment, it is noted that this procedure may have the following limitations: First, the IDA curve could flatten due to large residual DMs, which may not indicate the inability to sustain gravity loads necessarily. In addition, the IM-based and DM-based criteria are subjective limit-states relying on some assumed threshold values instead of the actual occurrence of dynamic instability. Therefore, the collapse capacity (both in terms of IM and DM) identified by these criteria could be sensitive to the assumed threshold values. In other terms, depending on the assumed value, these criteria could provide different evaluations of collapse capacity, which may not be the actual capacity against dynamic instability necessarily. Moreover, IDA curves may show characteristics in which the collapse criteria are breached, but then the structure remains stable at higher levels of loading. In that case, the aforementioned criteria may provide more than one collapse capacity for the applied ground motion that makes collapse capacity assessment elusive.

It is noted that existing approaches often use maximum (peak) response of the structure as the damage measure such as maximum inter-story drift. Since such peak responses can vary in the structure, one may obtain different estimation on damage states, e.g., light, moderate, severe damage and collapse, depending on the selected location at which the peak response is measured. To address this issue, it is desirable to evaluate cumulative response measure for the global system instead of measuring local peak responses only. Since the cumulative measures are load-path dependent, they are expected to help consider the damage history and pattern due to cyclic seismic loading. Accumulated plastic deformation and the hysteretic energy are commonly used for calculating cumulative damage indices [3–6]. However, most of these cumulative measures are usually assessed only at local level, and thus they are most appropriate for evaluating losses in resistance of individual elements prior to collapse rather than the global system.

This paper presents an energy-based collapse analysis of structures at the system level to identify global dynamic instability of building structures under variable seismic excitations. Since energy parameters at the system-level are aggregated quantities considering redistribution and variation of each individual component-damage within the structural system, they provide global information to represent cumulative structural damage due to cyclic loading up to and including collapse. In this work, nonlinear dynamic analyses are first performed for three experimental case studies for steel frames reported in the literature using OpenSees, an object-oriented software framework developed by Pacific Earthquake Engineering Center (PEER) [7]. Using the OpenSees computational models validated by these corresponding experimental results, a parametric investigation is conducted to develop a new energy-based collapse limit-state for planar frames under horizontally applied seismic loadings to identify dynamic instability due to loss of structural resistance against the gravity loads. The selected case studies are then used to test the new collapse limit-state. Collapse evaluations by the new collapse criterion are then compared to those resulting from typical use of IDAs employing either DM-based or IM-based criteria. In particular, sensitivity analyses are performed on the assumed threshold values used in the conventional criteria to clearly demonstrate the merits of the proposed energy-based collapse criterion.

## 2. Validated computational simulations of collapse

In order to develop a new collapse limit-state for more reliable structural collapse assessment under cyclic dynamic loadings, it is necessary to build validated computational models that simulate structural collapse accurately. This is because it is impossible to obtain enough amount of real or experimental data required to develop such a collapse limit-state. This study selected three sets of steel frame experimental shake-table tests by Kanvinde [8], Rodgers and Mahin [9], and Lignos et al. [10] to develop validated computational models with 1-story, 2-story, and 4-story structures, respectively, representing three examples of ductile steel frames with different geometries, load settings, hysteretic behaviors (see Table 1). While the ductile-baseline (DB) case study by Rodgers and Mahin [9] has a first-mode dominant period of 0.65 s, the case studies by Kanvinde [8] and Lignos et al. [10] have a similar first-mode dominant period between 0.40 and 0.50 s, but all cases have different hysteretic behaviors resulting in different strength ratios and strain magnitudes. OpenSees models comparable to the models developed in the original experimental studies were developed for each test case study, and were then validated against the corresponding experimental tests results. A sidesway collapse mechanism (i.e., significant growth of lateral story drifts under seismic forces) was the dominant failure mode in the collapse experiments.

### 2.1. Basic assumptions for collapse simulations

Prior studies on collapse assessment of steel structures have often used macro-models incorporating softening responses to simulate the effects of significant yielding and fracture or cyclic deterioration, coupled with geometric nonlinear behavior [8–12]. This work uses macro-model formulations that reflect the models used by the experimentalists for consistency and successful validation. This study therefore focuses on developing two-dimensional nonlinear dynamic finite element models of the selected steel moment-resisting frames using elastic beam elements for the girders and columns, coupled with the use of uniaxial, zero-length moment-rotation relations at the element ends.

### 2.2. Collapse case studies

Of the three selected experiments [8–10] used to validate the computational models for establishing collapse criteria [13,14], two of the test cases are described here in detail: a one-story steel frame test by Kanvinde [8] and a four-story steel frame test by Lignos et al. [10].

Kanvinde [8] conducted shake-table tests on a single-story steel specimen configuration measuring 12″ by 24″ [~30.48 cm by 60.96 cm] in plan (the longer dimension aligned in the direction of motion) and 10″ [~25.40 cm] in clear height to investigate dynamic instability of structures caused by earthquake excitations. The specimen configuration was in the form of four flat steel columns connected to a base plate. A steel mass on top served as a rigid diaphragm as shown in Fig. 1a. The columns have a cross-section of 1/8″ (along the direction of motion) by 1″ [~0.32 cm by 2.54 cm] with 1/2″ [~1.27 cm] holes drilled at the column ends