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A new efficient method for determining the collapse margin ratio using parallel computing

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ABSTRACT

The collapse margin ratio (CMR) is an important value in the FEMA P-695 process. However, determination of the CMR is computationally intensive and the duration for running a full incremental dynamic analysis (IDA) using serial computing to calculate the CMR can be prohibitive. In response to this restriction, a new efficient search method was created for finding the collapse margin ratio for a structural model using parallel computing. The proposed method does not require a full IDA and provides a significant decrease in the time required to determine the CMR compared to running a full IDA using serial computing. The new method is compared against similar methods for finding the CMR in parallel using both a four-story buckling restrained braced frame and a four-story steel moment resisting frame. Recommendations for overcoming convergence issues are discussed to aid in the application of the search method.

1. Introduction

Incremental dynamic analysis (IDA) [1] has become a popular method for assessing the variability in response of a building structure subjected to earthquake loading. The collapse results from the IDA are fit to a statistical distribution to quantify the collapse variability. The variability can then be characterized using a fragility curve, which is useful in the field of performance-based earthquake engineering (PBEE). The process of calculating the collapse fragility curve from IDA results is demonstrated in Fig. 1. IDA curves are constructed for a building structure from nonlinear dynamic analyses with all ground motions in a set, with each curve terminating at the ground motion intensity associated with collapse. The collapse intensity values from the full set of IDA curves (a) are then used to generate a statistical distribution, such as a lognormal distribution, to describe the collapse characteristics (b). The collapse distribution defines a cumulative distribution function (CDF) that represents the collapse fragility curve (c). However, completing an IDA with a ground motion set is computationally expensive, requiring potentially thousands of individual analyses of complex models, each taking anywhere from a few minutes to a few hours to complete. The FEMA P-695 Methodology [2] requires the determination of the collapse margin ratio (CMR), which is the ratio of the spectral acceleration for which 50% of the ground motions in a pre-defined record set cause collapse to the spectral acceleration at the maximum considered earthquake (MCE) ground motion intensity at the fundamental period of the structure. However, the response at only one point on the collapse fragility curve is also important in other instances. The basic safety consideration for buildings designed under U.S. codes is that a single class of buildings should not have more than a 10% probability of collapse when subjected to a suite of earthquake records that have been normalized and scaled to produce ground motions consistent with the MCE ground motion [3]. These ground motions are scaled to the "risk-targeted" MCE (MCE_R) ground motion, which is based on a 1% in 50 year collapse risk. This requirement can be checked by determining the collapse intensity associated with a 10% probability of collapse.

Calculation of the collapse intensity level for the single ground motion associated with a target collapse probability, such as the 50% collapse probability associated with the CMR, does not require the construction of complete IDA curves for all ground motions in the set. In addition, the procedure for an incremental dynamic analysis is conducive to the temporal gains of switching from serial to parallel analysis. The combination of the two former aspects of calculating the CMR and the characterization of collapse data using a fragility curve was the impetus for the new parallel CMR search procedure, referred to herein as the Fragility Search Method. Details of the procedure are presented, including the ability to provide an accurate collapse fragility curve while determining the CMR. The procedure is also compared against other parallel CMR search methods using example planar frames.

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2. Optimized incremental dynamic analysis

Incremental dynamic analysis [1] involves incrementally increasing an intensity measure (IM) corresponding to a scale factor on a single ground motion or a set of ground motions applied to a mathematical model of the structure while monitoring the response using engineering demand parameters (EDP). The time frame for completing a full IDA can be prohibitive, depending on the number of ground motions in the set, the complexity of the structural model, and the resolution of the IDA curves. Recognizing that a full and accurate IDA is not always necessary, several researchers have suggested approaches for extracting fractile IDA curves and collapse fragility curves using approximate methods without running a full IDA.

The most common approach for approximating IDA results from a building model is to correlate a complicated multiple-degree-of-freedom (MDOF) model to a single-degree-of-freedom (SDOF) model and run a full IDA on the SDOF model. The SDOF results are then correlated back to the MDOF model. Vamvatsikos and Cornell [4] correlated IDA results with a SDOF model capable of representing a quadrilinear backbone curve to generate fractile IDA curves. A fractile IDA curve represents a value of the distribution of IDA curves for which a fraction of the full set of IDA curves lie below it at every EDP value [1]. The pushover curve from the MDOF model was correlated to the SDOF model using the SPO2IDA software [5]. Hamidia et al. [6] presented a similar method in the context of the FEMA P-695 Methodology [2] for finding the CMR. Instead of running dynamic analyses on the SDOF model, the CMR for the corresponding SDOF model was found by interpolating tabulated results based on the results from a range of possible SDOF models. Azarbakht and Dolsek [7] used the SDOF model corresponding to the MDOF model to determine a precedence list of the records in the ground motion set for finding fractile IDA curves. The method, known as progressive incremental dynamic analysis, used a genetic algorithm and a simple recursive procedure to find the most influential individual IDA curves. Individual IDA curves from the MDOF model were then constructed and combined from the precedence list until the change in the fractile IDA curve was below a specified tolerance. Theophilou and Chryssathopoulos [8] presented a similar method for optimally choosing a reduced ground motion set compared to random selection of ground motion records for an IDA. However, the methods that relate SDOF and MDOF models are only applicable to first-mode dominated structures and are sensitive to the lateral force distribution used to calculate the pushover curve for the MDOF model.

Liel and Tuwair [9] presented a "guess and check" technique for directly calculating the median collapse spectral acceleration for a structure subjected to a set of ground motion records without running an IDA. Using an initial estimate for the median spectral acceleration, the associated probability of collapse was calculated by running dynamic analyses with all ground motions scaled to the spectral acceleration. A step size was applied to the spectral acceleration and the process was repeated until the lowest median collapse spectral acceleration was found.

Eads et al. [10] presented a different approach for approximating the collapse behavior of a structural model. Assuming the collapse distribution follows a lognormal cumulative distribution function (CDF), the collapse fragility curve was approximated using the collapse probability at two intensity levels. However, the intention of the approximate fragility curve was to compute the mean annual frequency of collapse, not to determine an accurate description of the collapse characteristics of the structural model subject to the set of ground motions.

3. Parallel incremental dynamic analysis

Because of the large number of analyses required for an IDA, parallel computing is useful for reducing the total analysis time. A natural parallel approach is a divide and conquer algorithm [11]. At each intensity level, multiple analyses involving different ground motions can run concurrently as they are mutually independent. The results from each processor are then compiled to determine the direction of the next step in the analysis. Vamvatsikos [12] presented a method for calculating the IDA curve for an individual ground motion using parallel computing with a hierarchy of master and slave processors. Each processor was responsible for computing a single point on the IDA curve. The algorithm consisted of a "hunt-up" phase, in which the intensity factor applied to the ground motion was incrementally increased at a quadratically accelerating rate until the collapse point was bracketed, and a "fill-in" phase, in which the EDP was determined at intensity factors in the gaps of the IDA curve. The collapse point was then determined using a 1/3–2/3 bisection operation. However, the algorithm did not directly search for the IM associated with a certain collapse probability.

When determining the intensity factor associated with a specific probability of collapse, the full IDA curves are unnecessary. Instead of generating response results for all records in the ground motion set, the problem becomes a search for the collapse intensity of the ground motion associated with the probability of collapse. For example, finding the ground motion intensity value associated with 50% collapse for a set of 44 ground motion records only requires calculating the collapse intensity value associated with the 22^{nd} ground motion that causes collapse. However, this ground motion is rarely known a priori, so the other ground motions must also be used to guide the analysis. The following sections describe common algorithms for determining the collapse margin ratio of a

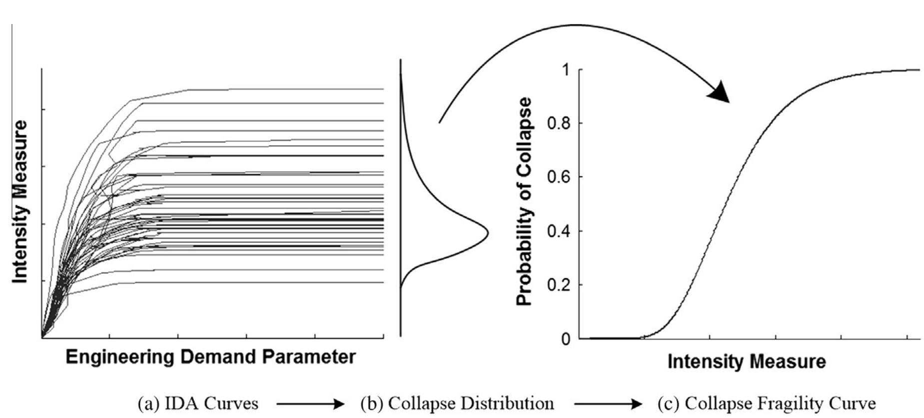

Fig. 1. Relationship between IDA collapse results and collapse fragility curve.