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Mainshock – Aftershock Interaction Diagram for a 3D Plan-Asymmetric Structure

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The main objective of this paper is to present an application of a methodology for development of mainshock-aftershock interaction diagrams. A mainshock-aftershock interaction diagram corresponds to a capacity curve that shows the aftershock spectral accelerations at a fundamental period of the structure that lead to the structure to fail after the structure has been subjected to a mainshock, which did not lead to failure. In this context, failure is to be read as “exceeding a given limit state”, which can correspond to a service level or ultimate limit state. This mainshock-aftershock curve is denoted as a capacity interaction diagram, or interaction diagram in short, since any pair of spectral accelerations that fall within the interaction diagram is a non-failure point, while any point falling outside of this curve is a failure point.

The methodology used to develop the mainshock-aftershock interaction diagram presented herein has been adapted from a framework for robustness assessment of building structures [1], which follows the definition of the earthquake hazard at a site [2]. In this paper, a plan-asymmetric building is used as a case study to illustrate the application of the methodology. The case study corresponds to the SPEAR building [3], a reinforced concrete plan-asymmetric full-scale frame structure that was tested under pseudo-dynamic conditions and subjected to bi-directional seismic loading. A nonlinear finite element model is developed in the Open System for Earthquake Engineering Simulation (OpenSees) software, leading to sufficient accuracy to characterize the nonlinear response to collapse, and also providing reliable estimates of the residual displacements and loss in stiffness and strength. The building model is subjected to sequences of a mainshock followed by an aftershock. The damage caused to the building by the mainshock is evaluated by performing an incremental dynamic analysis (IDA) [4]. Based on the properties of the mainshock, the conditional aftershock hazard can be defined following Luco et al. [5], and consequently, artificial mainshock-aftershock sequences are herein used. These records are selected for a site in Los Angeles, California, USA. The damage resulting from mainshock and aftershock is evaluated for each sequence. In this study, 10 sets of historical bi-directional earthquake motion accelerograms are selected for the mainshocks and aftershocks. The earthquake motion inputs are considered to be acting in two possible orthogonal directions, i.e. fault-normal or fault-parallel component acting in the X-direction of the building model. At least 20 ground motion intensities are considered for the mainshock and aftershock IDAs. In all, 10 x 2 x 20 x 10 x 2 x 20 = 160,000 nonlinear time-history response analyses are performed. To reduce the total computational time required for obtaining all the results for this very large number of runs, an embarrassingly parallel computing framework was implemented at Oregon State University. This framework makes use of a batch-queue system called HTCondor (v7.8.0) [6].

Figure 1 shows the mainshock-aftershock interaction diagram obtained when one of the earthquake records is used for both the mainshock and aftershock. Whenever the square root of the sum of squares (SRSS) of interstory drifts in X- and Y-direction exceeds 5%, the structure is said to fail. The curve shown in this figure considers that the components of the aftershock were rotated by 90 degrees, to account for the fact that this corresponds to a far-field earthquake record. It can be seen that for increasing mainshock intensities, the aftershock spectral acceleration that lead to failure is reduced, since the mainshock induced damage reduces the capacity of the structure to sustain additional damage due to the aftershocks. In Figures 2a) and 2b) the IDA curves for E1 (X_fP; Y_fN) and E1(X_fN; Y_fP) are shown, while Figures 2c) and 2d) show IDA curves for mainshock-aftershock sequences which correspond to application of E1(X_fP; Y_fN) followed by E1(X_fN; Y_fP).

The results presented successfully illustrate the application of methodology for developing of the mainshock-aftershock interaction diagrams. Similar methodologies may be developed for other cascading hazards, such as earthquake followed by tsunami and earthquake followed by fire, even though the numerical analysis models are more complex.

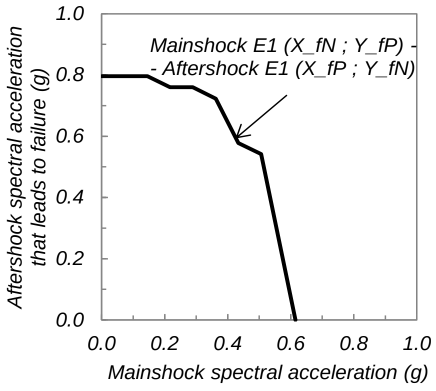
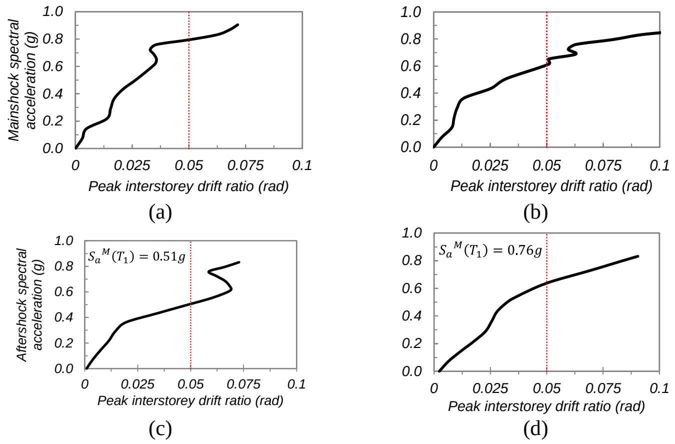


Figure 1 – Example of a mainshock–aftershock interaction diagram for earthquake E1



(a)

(b)

(c)

(d)

Figure 2 –Mainshock IDA curves for: (a) E1(X_fP; Y_fN), (b) E1(X_fN; Y_fP); and Aftershock IDA curves for mainshock spectral accelerations: (c) $S_a^M(T_1) = 0.51g$, and (d) $S_a^M(T_1) = 0.76g$

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