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DAMAGE ACCUMULATION IN A TWO-STORY WOOD-FRAME BUILDING IN SEQUENCES OF INDUCED EARTHQUAKES

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ABSTRACT

In this study, a nonlinear model of a two-story multifamily wood-frame residential structure is subjected to recordings of sequences of induced earthquakes in order to quantify changes in fragility and accumulation of damage throughout multiple earthquake loadings. Initial efforts consisting of ground motion selection, building design, numerical modeling, and preliminary results are presented. Damage is quantified through a seismic loss estimation procedure that accounts for damage to nonstructural and structural components of the building. Examining damage accumulation from sequential earthquake shaking enables us to explore how the occurrence of damage in an earthquake, even to relatively small levels, may increase a structure's susceptibility to collapse or damage in subsequent ground shaking. Ultimately, the goal is to compare damage fragilities and seismic losses as a function of the building's initial damage state.

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In this study, a nonlinear model of a two-story multifamily wood-frame residential structure is subjected to recordings of sequences of induced earthquakes in order to quantify changes in fragility and accumulation of damage throughout multiple earthquake loadings. Initial efforts consisting of ground motion selection, building design, numerical modeling, and preliminary results are presented. Damage is quantified through a seismic loss estimation procedure that accounts for damage to nonstructural and structural components of the building. Examining damage accumulation from sequential earthquake shaking enables us to explore how the occurrence of damage in an earthquake, even to relatively small levels, may increase a structure's susceptibility to collapse or damage in subsequent ground shaking. Ultimately, the goal is to compare damage fragilities and seismic losses as a function of the building's initial damage state.

Introduction

The deep disposal of wastewater associated with oil and gas production has been responsible for an increase in seismicity in parts of the U.S. This induced seismicity has dramatically increased the seismic hazard [1] and the risk to infrastructure [2] in places like Oklahoma and southern Kansas since about 2009. These induced earthquakes are generally of low magnitude ($\leq M_W$ 5.8), but are frequent and have often occurred in swarms. Swarms result from the migration of injected fluids and pore water pressures along already critically stressed faults [3].

This study aims to quantify how a building's seismic fragility changes and damage accumulates when subjected to a swarm of induced earthquakes. The study examines a two-story multifamily wood-frame building using nonlinear simulation models subjected to recorded ground motion sequences from induced earthquakes in dynamic analysis. Damage is quantified through seismic losses, *i.e.* repair costs, in an effort to assess damage even when the structural system itself may be undamaged or lightly damaged. Damage accumulation is examined from event to event in the swarm to explore how the occurrence of even small levels of damage in an earthquake may potentially change a structure's susceptibility to increased damage in subsequent shaking.

Ground Motion Selection

This study uses recorded ground motions from confirmed induced earthquakes in Oklahoma and

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southern Kansas for dynamic analysis. These ground motions are obtained from the Rennolet et al. [4] database. Our selection process first involved selecting a station recording with a geometric-mean peak ground acceleration (PGA) > 0.05g as a target, and then identifying a time window ±15 days around the target event. All of the earthquakes within this time window, and with an epicenter within a 25 km radius of the event producing the target record, are then considered for selection of motions to form a sequence. Ultimately, the two recordings with the largest PGA within these temporal and spatial windows are selected to combine with the target record to create a three-record sequence, keeping the same order as the events occurred. In total, 19 sequences are identified. In each of these, every earthquake has $M_W \geq 3.0$, and every motion has a geometric mean PGA ≥ 0.05g. Both horizontal components of these motions were filtered and processed according to standard recommendations, and applied simultaneously [5]. This extended abstract describes results from a subset of these sequences, considering selected two-motion sequences.

Building Design and Modeling

This study investigates a two-story multifamily residential light wood-frame building, a prevalent building typology in Oklahoma. This building was designed for "moderate seismicity" by the ATC 116 project team [6]. The building has a 48 ft. by 96 ft. footprint, divided into four individual family units. The exterior walls are framed with 2 in. x 6 in. lumber and the exterior faces are clad in stucco, with openings for windows and doors. The interior face of the exterior walls is clad with ½-in. gypsum wall board. The interior shear (party) walls are two lines of 2 in. x 4 in. framing separated by a 1 in. gap. These structural wood panel shear walls are finished with gypsum wall board on the face of the wall toward the interior of the unit.

The building was modeled in three-dimensions using Timber3D by Pang et al. [7], which was developed by Pang et al. [7, 8]. Timber3D captures the response of a flexible diaphragm, as well as the nonlinear seismic response of the shear walls and their connections [8]. The shear walls are modeled using a modified version of the Modified Stewart Hysteretic model [9], which has been calibrated to reflect characteristics of walls and nailing. Timber 3D captures geometric nonlinear responses, such as P-Δ effects. These features enable Timber3D to capture sidesway and eventual vertical collapse in the first story, the predominant failure mechanism in wood-frame structures [8, 9]. The first mode period of the building, *T*, is 0.38s (short direction). One-percent Rayleigh damping is assigned at the 1^{st} and 2^{nd} modes. Collapse is defined to occur when the first (above ground) floor displaces 10 inches downward.

Damage Accumulation Assessment Methodology

The accumulation of damage is studied by examining the structure's response to sequences of two motions. First, five damage states (DS) are defined, corresponding to various story drift ratios (SDR), as shown in Fig. 1a. These DSs are defined solely for the purpose of organizing the analysis; the values of SDR for each DS correspond to average thresholds at which damage occurs for wood walls [10]. We then create artificial sequences from the identified ground motions with different scaling combinations to explore the range of dynamic response. As shown in Fig. 1b, the first motion is scaled such that the building just reaches DS *i*. This scaled motion is combined with a second motion that is scaled through incremental dynamic analysis (IDA) [11].

Earthquake-induced losses assessed using the SP3 software [10]. Loss calculations are conditioned on the DS of the structure after motion 1. SP3 adopts the FEMA P-58 [12] methodology to gather inventories of building components, and building and component fragilities, which, when combined with dynamic analysis results, can be used to assess seismic losses representing the costs of repairing earthquake-induced damage. Fragility curves are also determined, relating the probability of the building entering a DS, as a function of motion intensity.

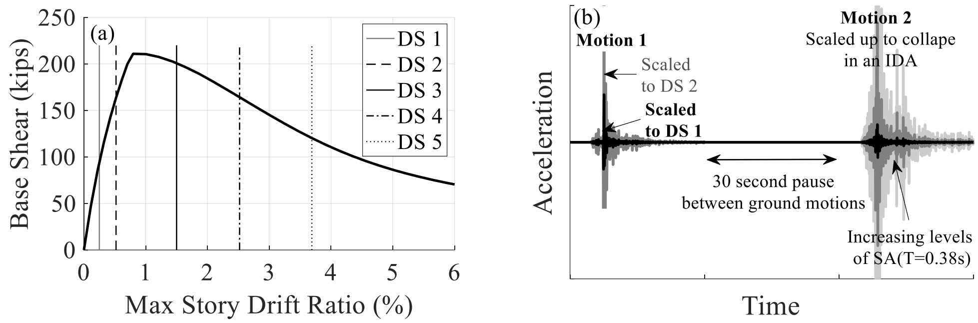

Figure 1. (a) Pushover curve for the building in the short direction, showing the DS defined in this study. (b) Example sequence of records representing an earthquake swarm.

Preliminary Dynamic Analysis Results

Fig. 2a presents fragility curves for the undamaged structure entering (or exceeding) DS 1 – 5. These fragility curves were derived through IDA. The first DS, corresponding to the cracking of stucco, occurs at a median spectral acceleration, SA(T=0.38s), of 0.31 g. Seismic losses amounting from structural components, electrical, plumbing, HVAC, and other nonstructural systems are shown in Fig. 2b. SP3 is used to compute economic losses as a function of SA, an increase of expected median seismic loss as a function of the SA and the DS. A significant jump in expected losses is observed for SA(T=0.38s)> 3g; above this level, the median residual drift tends to exceed 2%, necessitating replacement of the structure. As calculated in SP3, the total replacement cost for the building is $1.53M.

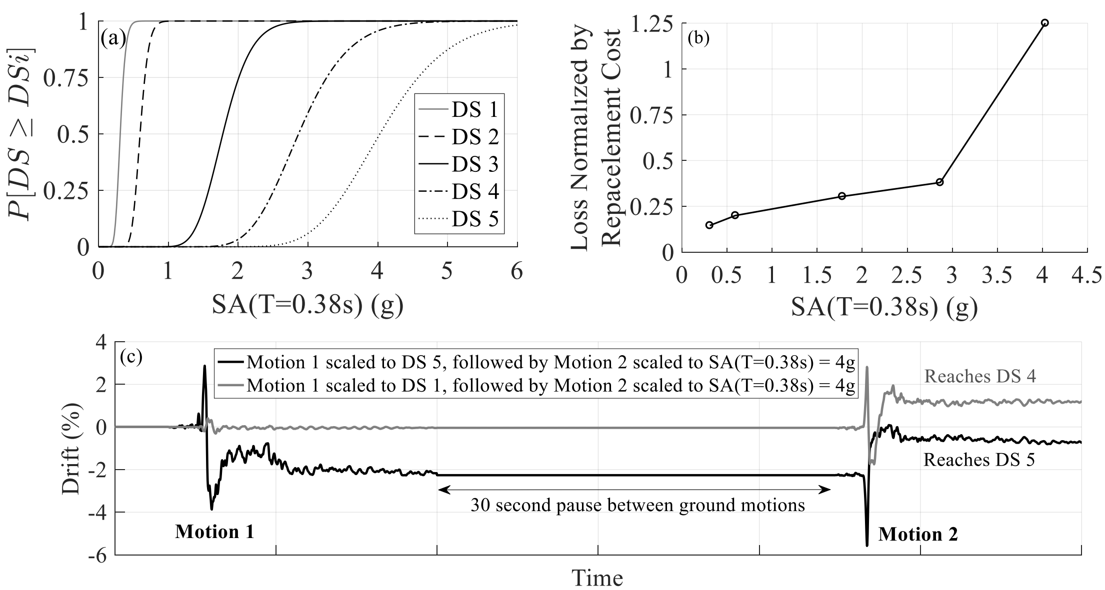

Figure 2. Preliminary dynamic analysis results showing: for undamaged structure (a) fragility curves for DS 1 – 5 and (b) seismic losses at each DS for the undamaged building, and for (c) first story drifts in a two-motion sequence.

Drifts obtained in a selected two-motion sequence are illustrated in Fig. 2c. Preliminary analysis found that, for a two-motion sequence, if the first motion causes the building to reach DS 5, maximum drifts are increased by 26% at a given SA level close to collapse, compared to the undamaged building. Further analysis is needed to examine these trends for more sequences, damage state levels, and three-motion sequences.

Conclusions

In this study, a nonlinear model of a two-story wood-frame residential structure is subjected to recordings of induced earthquakes. Initial assessments show that the structure's damage and expected seismic loss increase with ground motion intensity, as expected. In addition, the study shows that swarms of earthquakes may heighten susceptibility to damage in subsequent events, and that later events may exacerbate existing damage. Further work is needed to investigate the accumulation of damage in these structures due to multiple seismic events.

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