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A machine learning framework for assessing post-earthquake structural safety

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ABSTRACT

A machine learning framework is presented to assess post-earthquake structural safety. The concepts of response and damage patterns are introduced and incorporated into a systematic methodology for generating a robust dataset for any damaged building. Incremental dynamic analysis using sequential ground motions is used to evaluate the residual collapse capacity of the damaged structure. Machine learning algorithms are used to map response and damage patterns to the structural safety state (safe or unsafe to occupy) of the building based on an acceptable threshold of residual collapse capacity. Predictive models including classification and regression tree and Random Forests are used to probabilistically identify the structural safety state of an earthquake-damaged building. The proposed framework is applied to a 4-story reinforced concrete special moment frame building. Distinct yet partially overlapping response and damage patterns are found for the damaged building classified as safe and unsafe. High prediction accuracies of 91% and 88% are achieved when the safety state is assessed using response and damage patterns respectively. The proposed framework could be used to rapidly evaluate whether a damaged building remains structurally safe to occupy after a seismic event and can be implemented as a subroutine in community resilience evaluation or building lifecycle performance assessment and optimization.

1. Introduction

Assessing building structural and nonstructural component-level damage is a key step in the performance-based earthquake engineering (PBEE) framework [1–8]. Component damage characterization serves as the link between building structural response and the performance metrics (death, dollars and downtime) that are relevant to end-users. More recently, the importance of building-level limit states has been highlighted due to the growing emphasis on quantifying seismic resilience at the individual infrastructure and community scales [9,10]. Iervolino [11] defined post-earthquake building-level limit states based on the level of functionality (relative to before the event) that a damaged structure could support following an earthquake. These limit states were used to model the probabilistic recovery of functionality using state- and time-dependent Markov Chains. In the assessment of seismic resilience of a residential community, Burton et al. [12] proposed a set of building-level limit states, which are explicitly linked to post-earthquake recovery and functionality. Fragility curves were developed to link ground shaking intensity to the probability of exceedance of these limit states, which include functional loss, unsafe to occupy, demolition and collapse. Building-level limit states have also been used for lifecycle seismic performance assessment and optimization for structures, where retrofit strategies, repair cost, time and salvage value are considered [13].

Post-earthquake structural safety is key to determining whether a damaged building is safe to re-occupy, which is one of the key pieces of information needed by stakeholders immediately after an earthquake. ATC-20 [14,15] provides guidelines for post-earthquake visual inspection to rapidly evaluate building structural safety and assign corresponding green, yellow and red tags to buildings that are deemed safe to occupy, occupiable with restrictions and unsafe to occupy respectively. It has been widely used after U.S. earthquakes such as Loma Prieta, Landers, Northridge [15] and Hawaii [16] and adapted for use in many other countries around the world. Building on the work of Porter et al. [7], Mitrani-Reiser [17] used fragility curves to map continuous engineering demand parameters (EDPs) to discrete component-level damage states that have similar descriptions to the ones used

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Abbreviations: CART, Classification and regression tree; CP, Complexity parameter; DM, Damage measure; EDP, Engineering demand parameter; IDA, Incremental dynamic analysis; NRHA, Nonlinear response history analysis; PBEE, Performance-based earthquake engineering; RC, Reinforced concrete; ROC, Receiver operating characteristic; SMF, Special moment frame.

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in ATC-20. A “virtual inspector” was then used to probabilistically estimate building safety and assign corresponding tags based on the criteria in the first two tiers of an ATC-20 evaluation. The Mitrani-Reiser methodology was adopted in FEMA P58 [18,19] using a slightly different approach to link component-level damage to the likelihood that a building will be assigned an unsafe placard. For each structural and non-structural element, the median fraction of components (based on the total number in the building or a single story) in a particular damage state is estimated. The damaged building is assigned an unsafe placard if any of these values exceed a pre-defined triggering ratio. For example, the unsafe placard for steel special concentrically braced frames with wide flange braces could be triggered by any of the three scenarios: more that 60% of the components are in damage state 2 (brace has lost significant axial capacity), more than 40% of the components are in damage state 3 (brace and gusset are severely damaged with significant loss in stiffness and resistance), and more than 20% of the components are in damage state 4 (brace or gusset have fractured). It is important to note that the triggering ratios in FEMA-P58 are largely based on judgement and are not explicitly linked to the reduction in collapse safety of the damaged building.

Incremental dynamic analysis (IDA) [20–22] has been widely used to probabilistically assess the most critical building-level limit state of collapse. More recently, the reduction in the collapse capacity of mainshock damaged buildings has been used as a metric for assessing the post-earthquake structural safety and occupiability of damaged buildings. IDAs are performed using sequential ground motions to quantify the reduction in collapse capacity. Maffei et al. [23,24] proposed four post-earthquake occupiability criteria, which differ based on the metric used to quantify the reduction in collapse safety of the damaged building. Yeo and Cornell [25] used the time-varying aftershock hazard at a given site to compute an equivalent constant collapse rate, which decreases with time after the occurrence of the mainshock. The time-varying tagging scenarios are established based on the evolving collapse risk in the aftershock environment. The time-dependent tag could be changed from red to yellow and even green as time elapses. In the Maffei et al. and Yeo and Cornell studies, no direction link was made between component-level damage and the safety state of the building. Raghunandan et al. [26] quantified the increase in vulnerability to collapse of mainshock-damaged modern ductile reinforced concrete (RC) special moment frame (SMF) buildings. They also evaluated the extent to which different system- (transient and residual story drifts) and component-level damage indicators (e.g. beam and column plastic rotation) can serve as a proxy for the reduced collapse capacity. Single variable linear regression was used to link individual damage indicators to the residual collapse capacity. Burton and Deierlein [27] extended the Mitrani-Reiser and FEMA P58 approach by explicitly linking the component-level damage ratios that trigger an unsafe placard to the increase in collapse risk of the damaged building. However, the interaction between damage indicators was not considered in either of these two (Raghunandan et al., and Burton and Deierlein) studies.

Presented in this paper is a novel approach to assessing post-earthquake structural safety. Central to the newly proposed methodology is a machine learning framework for mapping building response and observable damage patterns to the residual collapse capacity of the structure, which is used as the criterion for assessing its safety state. The term “response pattern” is used to describe the distribution of peak global (e.g. residual and transient drifts) and local response (component deformations) demands obtained from nonlinear response history analysis (NRHA). Similarly, the term “damage pattern” describes the distribution of observable states of physical damage to key structural components obtained from damage simulation. Machine learning algorithms including classification and regression tree (CART) and Random Forests are used to build predictive models, which can probabilistically identify the post-earthquake structural safety state of the building based on its residual collapse capacity, given any unique response or damage pattern. To illustrate the overall methodology, a case study is conducted using a 4-story RC SMF building. Several applications are envisioned for the proposed framework. The model can be embedded in an electronic tool that can be used to supplement the judgement of field inspectors conducting post-earthquake building safety assessments. Observations of the distribution of component-level damage (or damage pattern) can serve as inputs into the model, which will provide probabilistic predictions of the safety state based on the reduced collapse capacity. For buildings instrumented to record, process and transmit structural response demands, the machine learning algorithm can be used to provide preliminary rapid estimates of the safety state of the building. The methodology can also be used to generate fragility curves for the “unsafe to occupy” building-level limit state, which can be incorporated into building or community resilience and lifecycle performance assessments and optimization.

2. Post-earthquake structural safety assessment

2.1. Overview of methodology

A schematic overview of the methodology used to assess post-earthquake structural safety is shown in Fig. 1. Starting with an intact structure, five distinct yet fully integrated steps are used to illustrate the assessment framework. The outcome of this assessment is the predicted structural safety state conditioned on the structural response demands (from instrumentation) and/or available observed physical damage (through field inspections).

The first step describes the process of using a set of “damaging” ground motions to create samples of the damaged structure from which response and damage patterns will be extracted. The response patterns or distribution of EDPs is obtained directly from NRHA. Subjecting the intact structure to a single damaging ground motion scaled to a specific spectral intensity will produce a single distinct response pattern. Multiple response patterns with different levels and distributions of response demands are obtained by using a suite of damaging ground motions scaled to incrementally increasing spectral intensities. Damage patterns are simulated using structural component damage fragility functions which relate local EDPs to the probability of exceeding a given damage state. A single damage pattern is described by each structural component assigned a single discrete damage state. Monte Carlo Simulation is used to generate multiple damage patterns for a single ground motion and spectral intensity. More details on generating the response and damage patterns and their relationship to the safety state of the building are provided in Section 2.3.

The collapse capacity of the damaged structure is assessed through the application of IDAs using sequential ground motions in the second step (Step 2). Each damaging record, which is used as the first ground motion in the sequence, is followed by an IDA using a set of “collapsing” ground motions. The median first-mode spectral acceleration corresponding to the collapse point $(\hat{S}a_{col,DMG})$ is used as the measure of residual collapse safety of the damaged building. In the third step, the collapse capacity of the intact structure is assessed by conducting single-record IDAs using the collapsing ground motions. The median collapse capacity $(\hat{S}a_{col,INT})$ is also used as the measure of collapse safety for the intact structure. Note that the dispersion or log-standard deviation of the collapse capacities, $\beta_{col,DMG}$ and $\beta_{col,INT}$, are also obtained but not directly used. The ratio of $\hat{S}a_{col,DMG}$ to $\hat{S}a_{col,INT}$ (κ) is used as a quantitative measure of the increased collapse vulnerability or the