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Nonmodel-based framework for rapid seismic risk and loss assessment of instrumented steel buildings

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ABSTRACT

This paper proposes a nonmodel-based framework for estimating story-based engineering demand parameters (EDPs) in instrumented steel frame buildings with steel moment-resisting frames (MRFs). The proposed framework utilizes a wavelet-based damage-sensitive feature and basic building geometric information to infer the building damage state at a given seismic intensity. The story-based EDPs are predicted with a reasonable accuracy compared to those predicted from rigorous nonlinear response history analyses that typically require the explicit use of a nonlinear building model. The efficiency of the proposed framework is demonstrated through a number of illustrative examples including actual instrumented steel frame buildings that experienced the 1994 Northridge earthquake in Los Angeles. It is shown that if the building content is known the proposed framework can facilitate building-specific seismic risk and loss assessment within minutes after an earthquake provided that the recorded floor absolute acceleration histories at discrete locations along the height of the building are accessible. The nonmodel-based framework is also extended at the city-scale through the development of generalized earthquake-induced damage and loss maps for the same earthquake event. The same framework can facilitate the decision-making for effective pre-disaster measures for earthquake disaster risk management of building assets.

1. Introduction

City-scale safety assessment in the aftermath of an earthquake is a challenging problem with vast socio-economic consequences. In that sense, visual inspections [1–4] have been historically employed. Such inspections may take months to complete and therefore earthquake-induced losses due to downtime can be considerable [1–4]. A number of researchers have utilized model-based approaches for the earthquake-induced structural and non-structural damage assessment (e.g., [5–11]). Although such approaches predict reasonably well story-based engineering demand parameters (EDPs) they typically require the explicit use of nonlinear building models and subsequently an appreciable time investment for the model validation. Therefore, such approaches cannot be used in the context of community resilience in which a rapid seismic risk assessment of building assets is necessary.

Vibration-based condition assessment [12–18] is an interesting alternative compared to *model-based* approaches conditioned that ambient vibration monitoring data is available and/or a seismic instrumentation program has been already established within the earthquake-affected region [19–21]. A challenge in this case could be that a densely arrayed sensing system may be required [22,23]. Noh et al. [17,18] proposed EDP indicators for *nonmodel-based* seismic vulnerability assessment of steel frame buildings by observing the changes in wavelet energies at a particular scale over time. In a more recent study, Hwang and Lignos [24] demonstrated that the wavelet-based damage-sensitive features (DSFs) can facilitate the seismic vulnerability assessment of buildings with fairly low instrumentation density. However, the challenge to establish the relationship between the wavelet energy shifting at a particular building frequency and the story-based building EDP estimates still remains. These EDPs are essential to facilitate earthquake-induced risk and loss assessment at a given seismic intensity.

In this paper, we propose a framework that facilitates the rapid seismic risk and loss assessment of instrumented steel frame buildings. The proposed framework is based on a nonmodel-based approach that combines concepts from structural health monitoring and performance-based earthquake engineering. The efficiency of the proposed framework is evaluated in three parts. The first part illustrates comparisons between the proposed framework and computationally intensive state-of-the-art approaches in predicting story-based building EDPs at a given seismic intensity. The second part utilizes the proposed framework to conduct a rapid seismic risk and loss assessment of an instrumented

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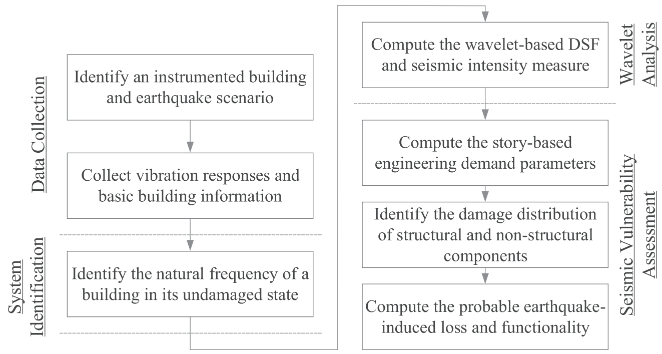

Fig. 1. Flowchart of the proposed framework for rapid seismic risk and loss assessment of instrumented steel frame buildings.

steel frame building that experienced the 1994 Northridge earthquake. The final part of the paper describes how the proposed framework can be extended at a city-scale in order to facilitate regional earthquake-induced loss assessment for emergency-response operations in the aftermath of an earthquake and pre-disaster measures for earthquake risk management.

2. Proposed framework for performance-based rapid assessment of steel frame buildings

This section presents a framework for performance-based rapid seismic vulnerability assessment of instrumented steel frame buildings. The emphasis is currently on steel frame buildings with moment-resisting frames (MRFs) as their lateral load-resisting system. Fig. 1 illustrates schematically the main components of the proposed framework. The first step involves the collection of basic information from the instrumented building of interest including the number of stories and the building height. In terms of recorded data, the absolute acceleration at the roof of the building is only required. Referring to Fig. 1, the proposed framework requires the identification of the dynamic properties of the instrumented building inferred to its undamaged state. This is further elaborated in Section 2.1.

Once the dynamic properties of the instrumented building are known, a refined wavelet-based DSF [17,24] is employed. The wavelet-based DSF is extracted from the measured absolute acceleration at the building roof. This is discussed in detail in Section 2.2. Referring to Fig. 1, the third component of the proposed framework includes the mapping of the computed DSFs with story-based EDPs along the height of the instrumented building. This mapping is achieved through multivariate regression equations that relate the wavelet-based DSFs and basic geometric building characteristics with story-based EDPs at a given seismic intensity (see Section 2.3). Finally, the earthquake-induced economic losses are computed. Referring to Fig. 1, depending on the density of the instrumented buildings within an earthquake-prone region a generalized loss map can be generated through the use of the geographic information system (GIS). The subsequent sections provide specific details of the main components of the proposed framework for seismic risk and loss assessment of instrumented steel frame buildings.

2.1. System identification

To compute the wavelet-based DSFs, the first natural frequency, f_1 of the undamaged state of a building is required. For this purpose, the use of ambient vibrations obtained before the earthquake occurs is preferred if available. Output-only system identification methods can be utilized because of the absence of a measured input excitation [13]. Otherwise, the last portion of the measured vibration recorded during a strong motion is considered as the vibration response of the undamaged instrumented building. The last portion is determined as the number of data points to provide best frequency resolution (0.097 Hz) for distinctive peaks in the power spectrum density diagram (PSD) estimation by applying a fast Fourier transform with a 1024-point Hann window [25]. In this paper, the autoregressive with exogenous term (ARX) method [14] is utilized for this purpose. The ARX model uses least squares to estimate the dynamic properties of a multi-degree-of-freedom (MDF) system from recorded absolute acceleration data in the discrete time domain. This model is mathematically defined as follows,

$$\sum_{i=0}^{M} \mathbf{A}_i \mathbf{y}(n-i) = \sum_{i=0}^{M} \mathbf{B}_i \mathbf{x}(n-i) + \mathbf{e}(n) \tag{1}$$

in which M is the model order of the ARX model; $\mathbf{x}(n)$ and $\mathbf{y}(n)$ are the p-dimensional input and q-dimensional output vectors, respectively; $\mathbf{e}(n)$ is the residue error vector; and $\mathbf{A}_i$ and $\mathbf{B}_i$ are $p \times p$ and $q \times p$ coefficient matrices of the autoregressive (AR) polynomial and exogenous (X) input. The model in Eq. (1) may be re-written as follows,

$$\mathbf{y}(n) = -\sum_{i=1}^{M} \mathbf{A}_i \mathbf{y}(n-i) + \sum_{i=0}^{M} \mathbf{B}_i \mathbf{x}(n-i) + \mathbf{e}(n) = \mathbf{\Phi}^T(n)\cdot\mathbf{\Theta} + \mathbf{e}(n) \tag{2}$$

in which

$$\mathbf{\Phi}^T(n) = [-\mathbf{y}(n-1) \ \cdots \ -\mathbf{y}(n-M) \ \ \mathbf{x}(n-1) \ \cdots \ \mathbf{x}(n-M)] \tag{3}$$

$$\mathbf{\Theta} = [\mathbf{A}_1 \ \cdots \ \mathbf{A}_M \ \ \mathbf{B}_1 \ \cdots \ \mathbf{B}_M]^{\mathrm{T}} \tag{4}$$

The parameter matrix, $\mathbf{\Theta}$ can be estimated based on the least square method as follows,

$$\arg\min_{\mathbf{\Theta}} J(\mathbf{\Theta}) = \arg\min_{\mathbf{\Theta}} \|\mathbf{y}(n) - \mathbf{\Phi}^T(n)\cdot\mathbf{\Theta}\|^2 \tag{5}$$

The AR coefficient and X input matrices are used to formulate the system matrix of equations. The dynamic properties of a MDF system are estimated by eigenvalue decomposition for the system matrix [14].

Due to random noise, it is common that spurious modes are induced [12,14]. In this case, a stable mode is estimated by changing the ARX model order. A stabilization diagram [12,14] is typically used for this purpose. From this diagram, stabilization occurs when the relative differences of the dynamic properties identified using two different model orders are not more than 5%, 10%, and 5% for the natural frequencies, the damping ratios, and the modal assurance criterion (MAC) of mode shapes [12] (i.e., convergence thresholds), respectively. Fig. 2 illustrates the stabilization diagram for the y loading direction of a 4-story steel frame building with moment-resisting frames (MRFs) tested at the E-Defense facility [26,27] estimated based on the single-input/three-output ARX method. Referring to Fig. 2, a relatively solid vertical line represents true modes. Moreover, the circled symbols represent the values that were converged to the thresholds for the frequency, MAC and damping ratio.

2.2. Wavelet-based damage-sensitive features

In order to develop an approximate method for rapid earthquake vulnerability assessment of steel frame buildings with MRFs, a non-model-based approach is employed. In particular, wavelet-based DSFs are utilized as proposed in [17]. The wavelet-based DSFs are computed based on the absolute acceleration response history recorded at the building roof. The DSFs are then interpreted as story-based EDP indicators by monitoring the change in wavelet-based DSFs at a given seismic intensity. This section briefly describes the theoretical background of the wavelet-based DSF that is utilized in this paper. Given a scale parameter $a > 0$, and time shift parameter b, the continuous wavelet transform can be mathematically described as follows,

$$C(a,b) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{a}}\psi^*\left(\frac{t-b}{a}\right)\mathrm{d}t \tag{6}$$

in which $f(t)$ is the response history data (i.e., the absolute acceleration time history in this paper); $\psi(t)$ is the mother wavelet function (the Morlet wavelet basis function [28] is used as a mother wavelet due to