*Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)*
*31 May – 1 June 2018, Singapore*
*Editor(s)* Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon
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# STRUCTURAL RESILIENCE THROUGH MODEL-BASED DATA INTERPRETATION: FROM BUILDING TO CITY-SCALE POST-SEISMIC ASSESSMENT

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Earthquake-design approaches in regions with low to medium seismic hazard often focus on the protection of inhabitants. Therefore, some structural damage is accepted. In addition, large parts of the building stock have usually been built without considering seismic limit states. Thus, earthquake events lead to large-scale post-earthquake assessments in order to determine the safety for occupancy of damaged buildings. Applying model-based data interpretation to earthquake-hit buildings has potential to increase assessment speed and objectivity. By accounting for uncertainties arising from multiple sources, a multiple-model approach for interpretation of ambient-vibration measurements is proposed. While ambient vibrations provide the engineer with quick and cheap measurement data, they are measurements of elastic behavior and therefore, interpretation for post-earthquake assessment must be done with great care. Outcomes of visual inspection and ambient-vibration measurements are combined in order to increase the knowledge of earthquake vulnerability of deteriorated structures and this leads to a measure of structural resilience. First, the applicability and utility of such an approach are shown for a single building. Then, we discuss opportunities (such as additional comparisons with similar buildings in a district) and limitations (high numbers of buildings to assess may result in excessive simulation times) that result from scaling the methodology up to assess entire cities.

*Keywords*: Structural resilience, Model-based data interpretation, Post-earthquake assessment, City-scale seismic evaluation, Error-Domain model falsification.

## 1 Introduction

Although advanced building codes have been developed over the past decades, earthquakes continue to be a threat for built infrastructure. Recently, the engineering community has introduced the concept of resilience against major disasters, such as earthquakes (Cimellaro et al., 2010). Cities are complex systems that are vulnerable to natural threats (Godschalk, 2003) and housing plays a major role regarding the resilience of a community. However, in regions with low to moderate seismic hazard, design practice focuses on the safety of the inhabitants and does not guarantee that buildings will stay elastic and undamaged during an earthquake. In, addition the risk of earthquake sequences demands a rapid assessment of the residual capacity of buildings in order for the inhabitants to safely stay in their houses.

Current practice for post-earthquake assessment of buildings relies mostly on visual inspection to tag buildings as being either safe or unsafe for occupancy. However, visual inspection has the drawbacks of being potentially subjective and non-homogeneous (Galloway et al., 2014; Lin et al., 2017) and of multiple inspections of the same building slowing down the post-earthquake assessment process, either due to non-conclusive inspections or due to aftershocks that require additional inspection. In addition, visual inspection provides an indication of building behavior during an earthquake, rather than a prediction of the capacity of a building to withstand future earthquakes.

Model-based measurement interpretation of earthquake-damaged buildings has the potential to reduce uncertainties regarding the residual capacity of earthquake-hit structures to withstand seismic actions. Thus, the resilience of a building, being the capacity to rapidly clear the building for occupancy, can be enhanced using measurements. Ambient vibrations are inexpensive, passive and non-destructive, and thus are a particularly interesting data source. However, ambient vibrations are characterized by very low amplitudes of accelerations, and therefore only provide insights in the linear behavior range of buildings. Physics-based models are needed to extrapolate nonlinear behavior from linear measurements.

In this paper, the reduction in uncertainties on the residual capacity that can be achieved from measurement interpretation involving only post-earthquake measurement data is shown on a single mixed unreinforced-masonry reinforced-concrete building. A high-fidelity model is used to predict the behavior of an earthquake-damaged building under subsequent earthquake actions and the accuracy of the predictions is verified using measured behavior. Finally, based on the results for a single building, the potential and the challenges to extrapolate structural resilience to enhance the resilience of a network of buildings (city-scale) are discussed.

## 2 Structural resilience through model-based data interpretation

Modern earthquake-design requirements ensure that building occupants are safe during an earthquake. However, it is likely that in regions with low to medium seismicity, buildings will sustain damage from earthquakes. Therefore, a seismic event will trigger a large post-seismic assessment need. While assessing highly resilient or highly vulnerable structures is generally unambiguous, intermediate structures are subject to important assessment uncertainties, as shown in Figure 1. Also, the risk of immediate aftershocks increases the need for accurately assessing the residual capacity of damaged structures to withstand earthquake actions and thereby fulfill their function to provide shelter to the occupants.

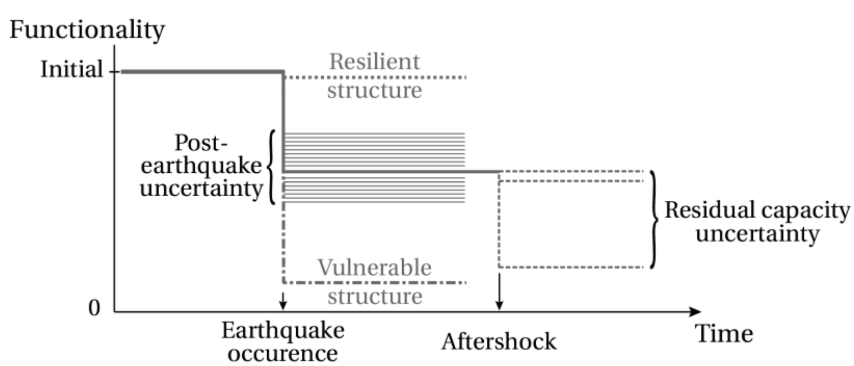


Figure 1. Uncertainties related to a structure hit by an earthquake event. Model-based measurement interpretation can help reducing the uncertainties on the residual capacity of a building.

Structural identification, which involves interpreting measurements using a physics-based model, has the potential to reduce the uncertainty regarding the residual capacity of damaged buildings. Therefore, the time between an event and the clearance for occupancy can be reduced, resulting in an enhanced resilience and a reduced need for provisional housing. In addition, reducing the uncertainty on the residual seismic capacity also results in less retrofitting activities, thereby increasing economic and ecological sustainability. Finally, in case a retrofitting is deemed necessary, structural identification of a physics-based model is useful to design targeted interventions.

### 2.1 *Error-domain model falsification*

Inferring parameter values of a physics-based model is an inverse task, thus multiple combinations of parameter values may explain the observed behavior. Therefore, a single parameter combination that is optimized to fit the measured data is ill-suited to perform predictions (involving extrapolation) with updated models. Error-domain model falsification (EDMF) is a model-based measurement-interpretation methodology that explicitly takes into account uncertainties from inevitable simplifications and omissions in modelling a structure.

EDMF has first been proposed by Goulet and Smith (2013) and has been applied to structural identification of several full-scale structures (Smith, 2016). EDMF is based on the principle that measurement data should ideally be used to falsify inappropriate model-predictions. Therefore, EDMF provides accurate identification and prediction estimates in presence of systematic uncertainties (Pasquier and Smith, 2015) even for nonlinear predictions based on sparse linear measurement data (Reuland et al., 2017).

Based on a combined uncertainty distribution, which is obtained by combining all sources of uncertainty linked to measurements and modelling, thresholds are calculated. These thresholds, $T_{low}$ and $T_{high}$, delimitate the shortest interval of the combined uncertainty distribution that cumulates in a predefined probability. Predictions with a physics-based model, g(·), that are obtained for an initial model population based on parameter combinations, $\boldsymbol{\theta}$, are compared to those thresholds, according to Eq. (1), where $y_i$ is the measured quantity *i*. The candidate model set is composed of the parameter combinations ($\boldsymbol{\theta}$) that verify Eq. (1) for all $n_m$ measured and modelled quantities *i*:

$$\forall i \in \{1, \dots, n_m\}: \; T_{low,i} \leq g_i(\boldsymbol{\theta}) - y_i \leq T_{high,i} \tag{1}$$

### 2.2 *Post-earthquake assessment with sparse measurement data*

Post-earthquake situations are often characterized by sparse structural data. Unless a detailed initial measurement campaign has been performed, little information is available regarding the modal properties prior to the earthquake. In addition, dense seismic measurement networks are rare in regions with low to medium seismic hazard, thus precise information regarding the seismic excitation at the base of a given structure is not always available.

Therefore, only post-earthquake modal properties and the outcome of visual inspection are used for structural identification in this contribution. A physics-based model is used to link the maximum displacement of a structure with the reduction of the fundamental frequency due to damage. In addition, the observed damage gives an estimation of the maximum displacement that a structure has undergone during an earthquake.

A link between observed damage (categorized as damage grades (DG) one to five as proposed by EMS98) and mechanical properties of a structure (yield and ultimate displacement capacity) have been proposed in the past by Lagomarsino and Giovinazzi (2006). Model instances (defined by the parameter combination, $\boldsymbol{\theta}$**)**, for which there is no overlapping between the range of maximum displacement resulting from the measured post-earthquake frequency ($\Delta_{f-drop}$, see Figure 2 at the top) and the range of maximum displacement that is compatible with the observed DG ($\Delta_{DG}(\boldsymbol{\theta})$, see Figure 2 at the bottom) are falsified. Thus, candidate models verify Eq. (2):

$$\Delta_{f-drop}(\boldsymbol{\theta}) \cap \Delta_{DG}(\boldsymbol{\theta}) \neq \emptyset \quad (2)$$

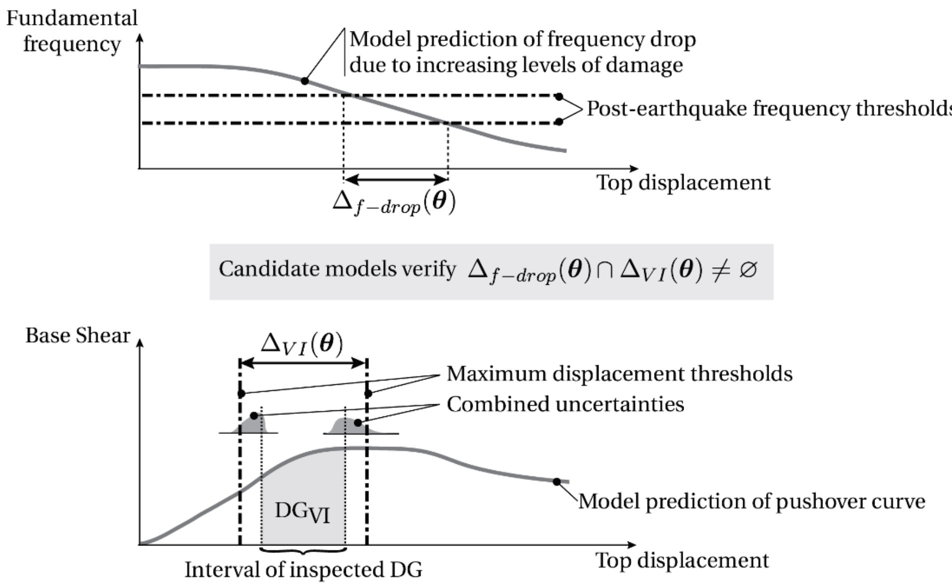


Figure 2. Combination of information from measured post-earthquake natural fundamental frequency and the damage grade (DG) observed from visual inspection.

## 3 Application to a tested building

The efficiency of using post-earthquake ambient-vibration measurements together with the outcome of visual inspection is validated on a half-scale laboratory specimen tested on a shaking table by Beyer et al. (2015). The building is a mixed unreinforced-masonry reinforced-concrete four-story building that has been tested for earthquakes with increasing levels of shaking (from 0.5m/s$^2$ to 15 m/s$^2$). The applied element method (AEM) has been used to build a three-dimensional model of the tested structure. AEM is based on nonlinear springs connecting small elements that model structural behavior (Karbassi and Nollet, 2013; Meguro and Tagel-Din, 2002) and is therefore particularly interesting to evaluate seismic behavior of masonry structures and the effect of damage on modal properties.

Given the large number of parameters that govern the behavior of such a high-fidelity three-dimensional model, a preliminary sensitivity analysis has been conducted to identify the 4 parameters that have the highest influence on the fundamental frequency as well as yield and ultimate displacements of the building: Young's modulus of masonry bricks, separation strain of mortar, Young's modulus of concrete, and compressive strength of concrete. Pushover curves with a linear displacement evolution are simulated for an initial model population composed of 100 instances. Although the AEM provides localized crack patterns, uncertainties linked to those patterns and the needs of a multiple-model approach resulted in a bilinear approximation of the predicted pushover curves to derive yield and ultimate displacements.

Based on Eq. (2), 90 out of the 100 parameter combinations for the laboratory specimen are falsified using the post-earthquake frequency (5.3Hz) and the observed DG2. The predicted DGs due to subsequent earthquakes resulting from the initial model population and the candidate model set are shown in Table 1. For the first subsequent shaking (with a peak ground acceleration (PGA) of 6.3 $m/s^2$) a DG3 has been observed following the test, while for the second shaking test (PGA of 14.8 $m/s^2$) a DG4-5 has been observed (Beyer et al., 2015). A major increase in precision in the predicted DGs can be observed after performing structural identification with scarce measurement data: the predicted probability of a DG3 increases from 42% to 95% for the first shaking and the probability of a DG4-5 increases from 68% to 100% for the second shaking. In this case predictions without performing model-based data interpretation tend to be non-conservative.

**Table 1.** Comparison of prediction accuracy for the two shaking table tests following ambient-vibration measurements with and without performing measurement interpretation. DGs that have been observed on the tested building are labelled *obs*.

| Predicted DG | Subsequent shaking at 6.3$m/s^2$ | | Subsequent shaking at 14.8$m/s^2$ | |
|---|---|---|---|---|
| | Initial model population | Candidate model set | Initial model population | Candidate model set |
| 2 | 50% | 0% | 22% | 0% |
| 3 | 42% (*obs*) | 95% (*obs*) | 10% | 0% |
| ≥4 | 8% | 5% | 68% (*obs*) | 100% (*obs*) |

## 4 Outlook on resilience of built environment at city scale

Several challenges are linked to upscaling the proposed post-earthquake assessment for increased resilience of entire communities. However, within a city multiple buildings can be gathered into similar construction types, which reduces simulation time. A major issue consists in attributing the correct type of resisting structure to each building, especially in a post-seismic situation characterised by limited access to the buildings. In the case of masonry buildings, knowing whether the slab is stiff or flexible is very important. In the past, decision matrixes based on several external parameters of buildings, such as balconies and roof structures have been proposed to attribute building typologies (Riedel et al., 2015) that can be used in a first rapid assessment of the city. In cases of regions with moderate to high seismicity, such as Switzerland, building types may have already been identified prior to a potential earthquake (Lestuzzi et al., 2016). Also, modern technology such as drones, thermal cameras and automated image recognition, may help to provide rapid post-earthquake assessments of entire cities and regions.

The precision of the prediction results can be increased based on learning conditional probability, as proposed by Goulet et al. (2015). However, they proposed a methodology that requires continuous measurement installations on the entire building stock to derive the frequency shift as a damage parameter. The goal of the proposed city-scale resilience analysis is to obtain in the immediate aftermath of an earthquake event an urban scenario of residual capacity of buildings, based on which they can be objectively tagged as safe for occupancy or not. The assessment at urban scale is based on extrapolating the results obtained on few measured buildings to the buildings of similar types. The precision of the predictions can be increased in the following days through measurements and detailed visual inspections on additional buildings.

## 5 Conclusions

In this paper, a methodology to use measured and observed information for rapid and reliable post-earthquake assessment is proposed in order to increase the resilience of buildings, which can ultimately be upscaled for the resilience of a city-scale building network. The following conclusions are drawn:

- The uncertainty related to the residual capacity of buildings can be reduced using post-earthquake measurements and observations.
- Error-domain model falsification is a powerful methodology to combine data sources, such as objective and precise post-earthquake natural frequencies as well as subjective and interval-based damage grades, in order to reach rational decisions related to resilience.
- Several compatible strategies are available to upscale the proposed methodology in order to increase earthquake resilience at city-scale.

## Acknowledgments

This work was funded by the Swiss National Science Foundation under Contract No. 200020-169026. The authors thank Prof. Beyer and the Earthquake Engineering and Structural Dynamics Laboratory of EPFL for sharing the test data.

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