Seismic Resilience Assessment of Instrumented Buildings: A Performance-based Monitoring Approach

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ABSTRACT

This paper presents a novel probabilistic performance-based monitoring approach for high-resolution seismic damage assessment and resilience quantification in instrumented buildings. The objective is to estimate seismic loss and functionality metrics, which can be integrated into multi-disciplinary community resilience models consisting of interdependent physical, social, and economic metrics. The proposed methodology begins with optimal sensor placement to measure the seismic response of an instrumented building. Then, a structural model-sensor data fusion is implemented using a nonlinear model-based observer to obtain reconstructed engineering demand parameters (REDP) and their estimation uncertainty. The mean and dispersion of REDPs are employed to quantify probabilistic seismic loss consistent with FEMA P-58 methodology, estimating downtime and total loss, which are two necessary parameters for creating component-based functionality curves. These curves define resilience as a function of loss due to extreme events and provide the necessary metrics for linking engineering models with social and economic impact models to estimate multi-disciplinary resilience metrics. The proposed methodology is demonstrated using data obtained from full-scale seismic testing of a wood-frame building conducted at the E-Defense facility in Japan.

INTRODUCTION

Natural catastrophic disasters such as the Turkey-Syria earthquakes that human society has faced in recent years have highlighted the immediate need to be prepared to quickly recover from a sudden and unexpected change in the community's technological, organizational, social, and economic status [1]. Due to the significant increase in population and industrial development in earthquake-prone areas, as well as the growing vulnerability of aging structures and infrastructure, structural resilience and risk assessment studies of civil infrastructure have significantly increased. In this regard, different conceptual frameworks such as risk assessment, recovery planning, and resilience analysis have been developed to mitigate and manage the consequences when the community requires immediate help to survive and recover in a short time. From a building-level

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perspective, the ability of a building to recover its normal functions as a result of an adverse event in a certain time from the damage induced by such a damaging event is called resilience within the existing literature [2,3].

The advancement of new technologies and data analysis methods provides new opportunities to improve the performance, resilience, and sustainability of structural and infrastructure systems. In recent years, instrumented buildings, equipped with sensing technologies, enabled engineers to more reliably monitor structural characteristics for seismic performance assessment [4, 5]. To effectively utilize the data obtained from monitoring devices, multidisciplinary studies need to interconnect resilience quantification techniques with smart system technologies to minimize risk and optimize the life-cycle cost of structural systems [6, 7]. For example, various monitoring data from different sources using advanced data analysis methodologies such as data fusion have been utilized to assess seismic damage and losses of bridges [8]. Nonetheless, there is still a lack of comprehensive studies to conduct cost-benefit research in order to study the beneficial application of these technologies in comparison to conventional methods.

This paper presents a novel probabilistic performance-based monitoring methodology for resilience quantification in instrumented buildings using optimal minimal sensing and nonlinear model-data fusion (NM-DF). By implementing monitoring systems, accurate assessment of demands and damage states, as crucial steps in component-based functionality estimation, can be reliably accomplished. This methodology consists of (1) measurement, (2) dynamic response reconstruction, (3) damage analysis, (4) loss and functionality analysis and (5) resilience quantification. The proposed methodology begins with optimal sensor placement to measure the seismic response of an instrumented building in a few limited locations. Then, a structural model-data fusion is implemented using a nonlinear model-based observer to obtain reconstructed engineering demand parameters (REDP) and their uncertainty. The mean and dispersion of REDPs are employed to quantify probabilistic functionality losses (e.g., repair cost and time) consistent with FEMA-P58 methodology for developing functionality curves. The applications of the proposed methodology is examined for a real-world case study of the 2009 NEESWood Capstone building full-scale tests conducted at the E-Defense facility in Japan.

SEISMIC FUNCTIONALITY ASSESSMENT

Resilience and its quantitative evaluation involve various meaningful and countable matrices which address a system's capacity to (1) withstand and recover when facing an adverse event such as a damaging earthquake [3]. Seismic resilience is commonly quantified as the integration of functionality (Q) measures over a certain control time. The functionality of a structure reflects its performance expressed by various measures such as repair cost, occupancy level, or asset value [9]. The seismic resilience (R) over a certain control time, t_C, after an abnormal disturbance such as an earthquake occurs at time t_0 is expressed as [6]

$$R = \frac{1}{t_c} \int_{t_0}^{t_0+t_c} Q(t)\, dt \tag{1}$$

To develop a functionality curve and quantify R from Equation 1, downtime and total loss are required. FEMA P-58 [10] provides a database of seismic consequence functions for different structural and non-structural components which are used to quantify the repair time and cost for each component as a component-based functionality assessment methodology. To enhance the high-resolution element-level estimation of these metrics, a recently developed conceptual framework, namely performance-based monitoring (PBM) has been proposed to quantify damage and functionality metrics based on minimally instrumentation of buildings.

THE PBM CONCEPT

The PBM methodology as shown in Figure 1 incorporates building monitoring data and advanced computational data fusion methodologies. This methodology allows for the reconstruction of different sets of engineering demand parameters (EDP) based on the choice of damage-sensitive features as well as fusion-based damage models to evaluate different performance measures of a building of interest [11]. It consists of (1) measurement, (2) dynamic response reconstruction, (3) damage analysis, (4) loss and functionality analysis, and (5) resilience quantification. The outcome of every step of the proposed concept is characterized by one of four generalized variables, including response measurement (M), EDP, damage measure (DM), and decision variable (DV). Using the Total Probability Theorem, the proposed framework equation is expressed by

$$p[\text{DV}] = \iiint p[\text{DV}|\text{DM}]\, p[\text{DM}|\text{EDP}]\, p[\text{EDP}|\text{M}] p[\text{M}] d\text{IM}.d\text{EDP}.d\text{DM} \qquad (2)$$

where $p[\mathrm{M}]$ is the probability density of the measurement set, and $p[\mathrm{EDP}|\mathrm{M}]$ is the conditional probability of experiencing a level of response parameter given measurement set M. The theory of the concept is explained in further detail as follows.

PBM-BASED FUNCTIONALITY ASSESSMENT

The PBM concept allows for the estimation of seismic loss and functionality metrics from estimated damage state probabilities based on reconstructed nonlinear fusion-based demand sets as REDPs. This method provides estimates of all relevant response quantities such as inter-story drifts and element forces, with their corresponding uncertainty using minimal sensing and model-data fusion. The estimation of displacement response, $\hat{q}(t)$ using a non-linear model-based observer (NMBO) is given by the solution of the following equation by

$$\mathbf{M}\ddot{\hat{q}}(t) + (\mathbf{C}_\xi + \mathbf{c}_2^T\mathbf{E}\mathbf{c}_2)\dot{\hat{q}}(t) + f_R(\hat{q}(t), \dot{\hat{q}}(t), z(t)) = \mathbf{c}_2^T\mathbf{E}\dot{y}(t) \qquad (3)$$

where $\dot{y}(t)$ is the measured velocity and $\mathbf{E} \in \mathbb{R}^{m\times m}$ is the feedback gain. Interested readers are referred to [12] for extra details regarding the theory and fundamentals of PBM.

The repair cost of seismic damages as a quantifiable monetary loss measure has been taken into account as a functionality indicator to develop seismic functionality curves [1]. Other indicators such as occupancy and asset values as a measure of functionality have been considered for developing functionality curves as well [9]. Given that loss

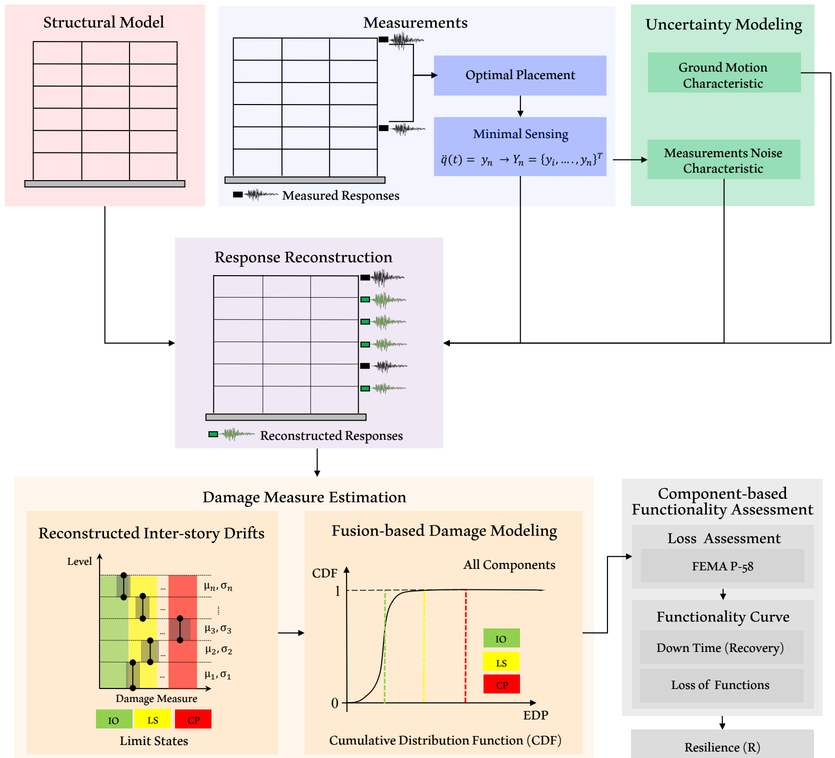


Figure 1. Summary of the proposed PBM-based methodology for building-level loss and functionality assessment.

is commonly quantified in terms of the monetary cost of repair or replacement, the full functional building is also valued in terms of the building's monetary replacement cost. As a result, using obtained REDPs from PBM, FEMA P-58 consequence function such as (1) repair cost and (2) repair time can be convoluted to model functionality curves and quantify the resilience of a structure.

CASE STUDY OF NEESWOOD CAPSTONE 6-STORY WOOD FRAME BUILDING

The proposed methodology is implemented on a six-story wood-frame building tested in a series of full-scale seismic tests in the final phase of the NEESWood project. The building was tested with various hazard levels including (1) test 3 (hazard level 50% in 50 years), (2) test 4 (hazard level 10% in 50 years), and (3) test 5 (hazard level 2% in 50 years). The hazard levels represent a set of tri-axial Northridge ground motions (recorded at Canoga Park). As shown in Figure 2, the building was instrumented with over 300 channels consisting of acceleration, displacement, strain, and optical tracking measurements [13].

RESULTS

In this section, the resilience of the case study building is quantified for three earth-

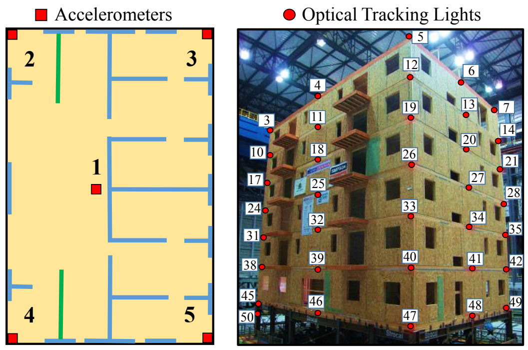
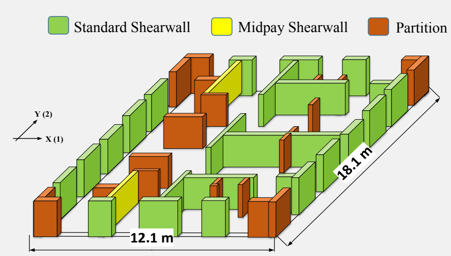


Figure 2. Instrumentation locations on NEESWood frame shake table test model: accelerometers in every floor (left); and optical tracking lights (right)

quake intensities. The performance-based engineering (PBE) software based on the Pelicun library is used to calculate functionality metrics [14]. A light-wood frame structure with shear wall structural components with a residential occupancy class is considered for loss assessment. Further details about the asset model and experienced intensities are shown in Figure 3. Specific considerations such as yield drift ratio to quantify residual drifts based on the FEMA P-58 method and extra details to implement loss assessment using PBE are described in the asset model as well.

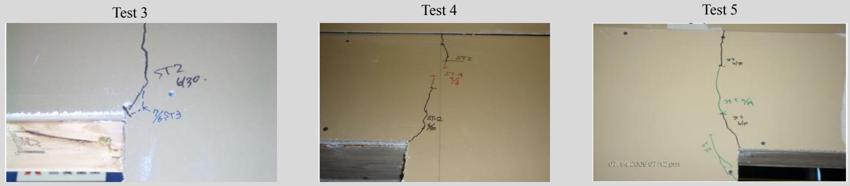
Asset Model



Parameters	
Stories	6
Total Area	14400 ft^2
Replacement Cost	1560000 $
Replacement Time	150 Days
Occupancy	Residential
Plan Area	2400 ft^2
Yield Drift Ratio	0.52
PID Truncation Limit	6 %
PFA Truncation Limit	2 g

Seismic Intensities

Test 3 Test 4 Test 5



Test 3: Very limited propagation of existing cracks; most cracks remained unchanged; cracking on exposed compression studs of Midply wall was observed but there is no sign of propagation; no detectable damage to structural members.
Test 4: Limited propagation of existing cracks; most cracks remained unchanged; minor cracking on ceiling GWB panel at very limited locations; no detectable damage to structural members.
Test 5: Propagation of existing cracks; local buckling of GWB panel near wall openings; new cracks observed on exposed compression studs of Midply wall; several nails showed sign of pulling out on Midply wall studs; the exterior shear wall panels were examined after the test, no structural damage was observed based on the inspection.

Figure 3. The asset model and seismic intensities experienced by building (for further details refer to [13])

COMPONENT-BASED LOSS ASSESSMENT

The FEMA P-58 methodology is used to quantify loss estimates required to develop functionality curves. Herein, the EDPs directly extracted from measurements as well as REDPs from the NMBO model are used as demand models for loss assessment [15]. These data including peak inter-story drift ratios (PID) and peak floor accelerations (PFA) are used to develop demand sets for 500 realizations using Monte Carlo (MC) simulations to evaluate the uncertainty of performance outcome. Once the EDP model is established, the asset model with building basic data including the structural and non-structural assets and their quantities should be established as well. The loss estimates (i.e., repair time and cost) as shown in Figure 4, required to develop functionality curves through a fully probabilistic process are calculated for three levels of ground motion intensities (e.g., seismic tests 3 to 5).

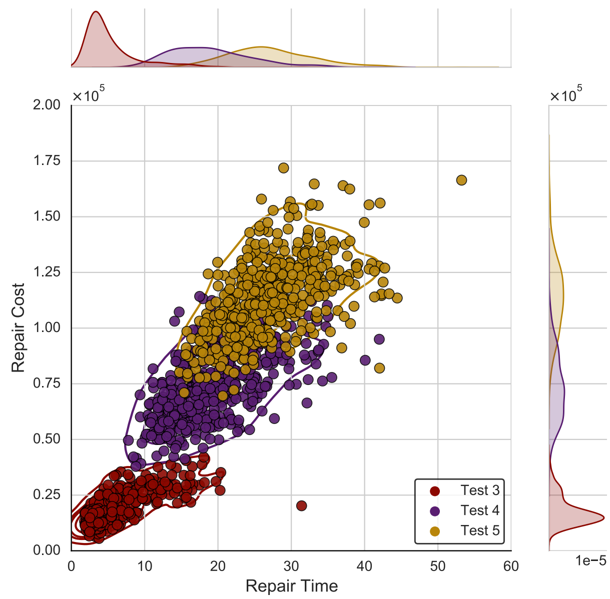


Figure 4. Repair time (parallel) and cost loss estimates using FEMA P-58 methodology from REDPs.

FUNCTIONALITY CURVES

The calculated loss results for quantification of the functionality metrics are only with consideration of shear walls and partitions in this study. Only three different types of shear walls were used as physical assets in the building. However, during experimental testing, the mass of non-structural components was added on floor levels using steel plates but for the current study are not considered for loss assessment. The building shows 99.9%, 98.9%, and 98.2% resilience under the seismic test 3 to 5, respectively. Other resilience dimensions such as robustness and rapidity quantified from functionality curves are set out in Table 1 as well. In various seismic tests, the building sustained approximately 27800 ($), 94300 ($), and 134730 ($) monetary loss (i.e., 90^{th} percentiles of all realizations) with repair as a measure of functionality. For example in the test 5, as shown in Figure 5, the building sustains 8.64% repair functionality loss and 35 days of repair time.

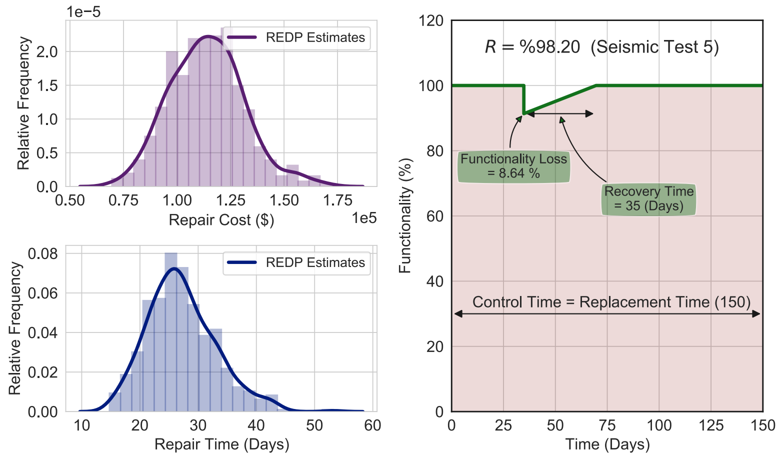


Figure 5. The relative frequency of repair cost and time (left); and functionality curve for seismic test 5 (right)

TABLE I. Resilience, robustness, and rapidity indices for 90^{th} percentile monetary repair loss and time considering a parallel repair plan for earthquake intensity 1, 2, and 3.

Seismic Test	Resilience (%)	Robustness (%)	Rapidity (%/%)	Repair Cost ($)	Repair Time (Days)
3	99.9	98.21	0.24	27822	11
4	98.9	93.95	0.33	94312	27
5	98.2	91.36	0.37	134730	35

CONCLUSION

This paper implements a recently developed performance-based monitoring (PBM) concept for probabilistic building-level seismic resilience quantification in instrumented buildings. The methodology allows quantifying functionality metrics to develop functionality curves. This is achieved by optimal sensor placement to measure the seismic response of an instrumented building. Then, a structural model-sensor data-fusion is implemented using a nonlinear model-based observer to obtain reconstructed engineering demand parameters (REDP) and their dispersion. The mean and dispersion of REDPs are employed to quantify probabilistic seismic loss consistent with FEMA-P58 methodology, estimating downtime and total loss, which are two necessary parameters for creating functionality curves. The proposed methodology is demonstrated using data obtained from full-scale seismic testing of a wood-frame building conducted at the E-Defense facility in Japan.

Through estimation of seismic loss and functionality metrics, which can be integrated into multi-disciplinary community resilience models this methodology can help engineers to accurately estimate seismic damages and consequences for resilience-informed functionality assessment and making decisions with specific attention to post-event re-occupancy and functional recovery planning. Future studies will focus on implementing the methodology with consideration of non-structural components and other parameters influencing the resilience such as delays (a.k.a. impeding factors) that can be incurred before the initiation of repair works, due to factors such as permitting, financing, inspections, etc.

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