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Optimal Sensor Placement and Probabilistic Engineering Demand Parameter Reconstruction for Seismic Monitoring and Risk Modeling

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ABSTRACT

This paper presents a methodology for optimal sensor placement and reconstruction of seismic engineering demand parameters (EDPs) in instrumented buildings to perform seismic structural monitoring and loss modeling. The framework links the number and layout of instrumentation to the accuracy of estimating seismic EDPs and their uncertainty to place sensors in locations that minimize the uncertainty for EDP reconstruction. This minimization can be achieved by selecting an optimality criterion based on the variance of a user-defined objective function related to the state of the structural system (e.g., displacements and inter-story drifts). The estimation of seismic EDPs is performed using a nonlinear model-data fusion approach which combines the measurements and a structural model to enhance the model's response estimation accuracy. The mean and dispersion of estimated EDPs are subsequently used to quantify seismic loss consistent with FEMA-P58 methodology. The proposed approach is illustrated using the measurements from full-scale seismic shake table tests of a six-story light-wood frame building structure conducted at the E-Defense facility in Japan.

Keywords: Seismic Monitoring; Loss Modeling, Model-Data Fusion, Response Reconstruction, Instrumented Buildings.

INTRODUCTION

The decision-making process regarding adverse events such as damaging earthquakes in terms of planning, maintenance, and resource allocation involves challenging problems. Despite the development of tools and frameworks for optimal decision making the officials and decision makers still can be seriously challenged when an unfavorable scenario such as a Turkey-Syria catastrophic earthquake takes place. The scope of the humanitarian response has not yet been sufficient to fulfill the tremendous needs of the displaced families and children who have endured exacerbated situations weeks after the deadly earthquake struck Turkey and Syria. The advancement of new technologies and data analysis methods can assist decision-making in the aftermath of such catastrophic events, where immediate emergency planning is required. Incorporation of modern technologies can significantly enhance decision-making from a building-level [1] or regional-level [2] perspective, allowing for notable cost-efficient and insightful crisis management. Efficient seismic risk assessment and mitigation, critical for the emergency response have been used in a variety of methodologies with the common aim of evaluating the social, environmental, and economic implications of damage to structures vulnerable to seismic extreme events. Among these methodologies, seismic loss assessment at a variety of resolutions has provided valuable information for city officials, economists, and engineers to make well-informed and imminent decisions for planning, maintenance, and resource allocation.

Seismic loss assessment methodologies associated with damaging earthquakes are developed to measure the seismic performance of structures with more meaningful and measurable metrics such as direct monetary losses. Performance-based earthquake engineering (PBEE) method is referred to as the most cited method with building and component-specific damage functions and data that relates structural performance with countable loss measures such as monetary loss [3]. On the other hand, from a broader perspective Hazus loss estimation methodology developed by Federal Emergency Management Agency (FEMA) includes losses broader than PBEE such as losses due to ground failure, damage to lifelines and transportation systems, inundation, and fire following earthquakes [4] as well as building-specific loss assessment method. Building-level seismic loss assessment, it is possible to use both the Hazus Style and the loss assessment methodologies such as the Pacific earthquake engineering research center (PEER) PBEE provided in several volumes (FEMA P-58).

In the past two decades, researchers and engineers have recognized the importance of seismic instrumentation for quantitative and rapid performance assessment of buildings during and immediately following earthquakes [5-8]. Although some researchers have used direct measurements to calculate seismic losses [9], a comprehensive framework for putting direct building measurements into loss assessment practice is still lacking. A recently developed performance-based monitoring (PBM) concept addresses the drawbacks within FEMA P-58 and Hazus methodologies when the monitoring data is available [10]. This methodology can estimate high-resolution element-level damage measures with a wide range of damage-sensitive features including inters-story drifts, element-by-element ductility, energy dissipation, and damage indices. Additionally, the peak inter-story drifts (PID) can be used to obtain the probability of exceeding various limits states using fusion-based damage models which are probability and cumulative distribution functions of PID reconstructed using first and second moment (i.e., mean and variance) estimates of PIDs.

This research presents a methodology for the estimation of consequential seismic losses using optimal minimum sensing and nonlinear model-data fusion (M-DF) from the recorded and reconstructed structural responses based on the PBM concept. By implementing monitoring systems and processes, accurate assessment of demands and damage states, as crucial steps in loss estimation, can be reliably accomplished. The accuracy of conventional loss assessment methodologies can be significantly improved by minimal instrumentation of building structures to measure and analyze their dynamic response and estimate system- and element-level seismic damage measures. The proposed PBM methodology consists of 1) measurement, 2) dynamic response reconstruction, 3) damage analysis, and 4) loss analysis. In this study, the direct engineering demand parameters (EDPs) and reconstructed EDPs (REDPs) based on the PBM concept are used for developing performance models with consequence functions such as repair cost and time. The applications of monitoring data and the PBM concept with specific attention to seismic demand modeling using optimal sensor placement with damage and loss functions of FEMA P-58 are examined for a real-world case study of the 2009 NEESWood Capstone building full-scale tests conducted at the E-Defense facility in Japan.

The paper begins with a section describing the loss assessment methodologies. Then in the following subsections, different loss assessment methodologies such as FEMA P-58 and PBM-based loss assessment are presented. The first section of the loss assessment describes building performance models described in FEMA P-58. These sections describe damage and loss models specified in FEMA P-58, such as fragility data and consequence functions. The following section describes the loss assessment presented by PBM with the incorporation of monitoring data into this approach. Finally, the proposed methodology is validated using real seismic response measurements from the 2009 NEESWood Capstone building full-scale tests conducted at the E-Defense facility in Japan. The paper ends with a conclusion on the results and future studies.

LOSS ASSESSMENT

The exposure of critical infrastructure to natural hazards such as earthquakes can cause severe direct and indirect social and economic cascading consequences. Countable loss indicators like monetary losses are used as a meaningful measure of building performance against seismic consequences. In general, seismic losses with different consequences such as monetary losses, repair cost and time, casualties, functionality loss and downtime, and other types of consequences can be estimated through different methodologies. Structural integrity and risk assessment of civil infrastructure have been developed in order to assess and quantify physical damage, functionality, and consequences using probabilistic components and system-level fragility and vulnerability functions [11]. Interest in the risk and resilience of civil infrastructure has led to a growing body of literature on seismic impact assessment and loss estimation methods. Researchers have taken different approaches to connect these fields with the common goal of estimating the social, environmental, and economic impacts of damage to buildings subject to seismic events. Seismic loss assessment methodologies have been developed and implemented in various resolutions ranging from building- to regional levels. In general, loss estimation methodology is a convolution of hazard risk, damage values, and vulnerability [12]. In the following, building-level seismic loss assessment is evaluated in further detail.

Building-level Loss Assessment

Building assets at risk and vulnerable to earthquake shaking should be assembled and considered to quantify seismic losses and consequences. The common methodologies for building-level loss assessment are developed within FEMA P-58 different volumes and the Hazus method. Several approaches to damage and loss modeling have been utilized by both methodologies. Building models with specific basic data, occupancy class, specific structural components and demands, and vulnerable non-structural components can be considered for loss assessment within both methodologies. Fragility specifications as an important part of a building damage model in both methodologies, including damage states and fragility functions, can provide vital information to map damage measures to the probability of exceeding damage states to estimate consequential losses such as direct repair cost and time. Every structural building built of various components' quantity and contents can be evaluated based on fragility and consequence data for a typical building within these methodologies. In this research, only the key steps and distinguishing factors of the FEMA P-58 loss calculation methodology and the advantage of PBM-based loss assessment are discussed in the following.

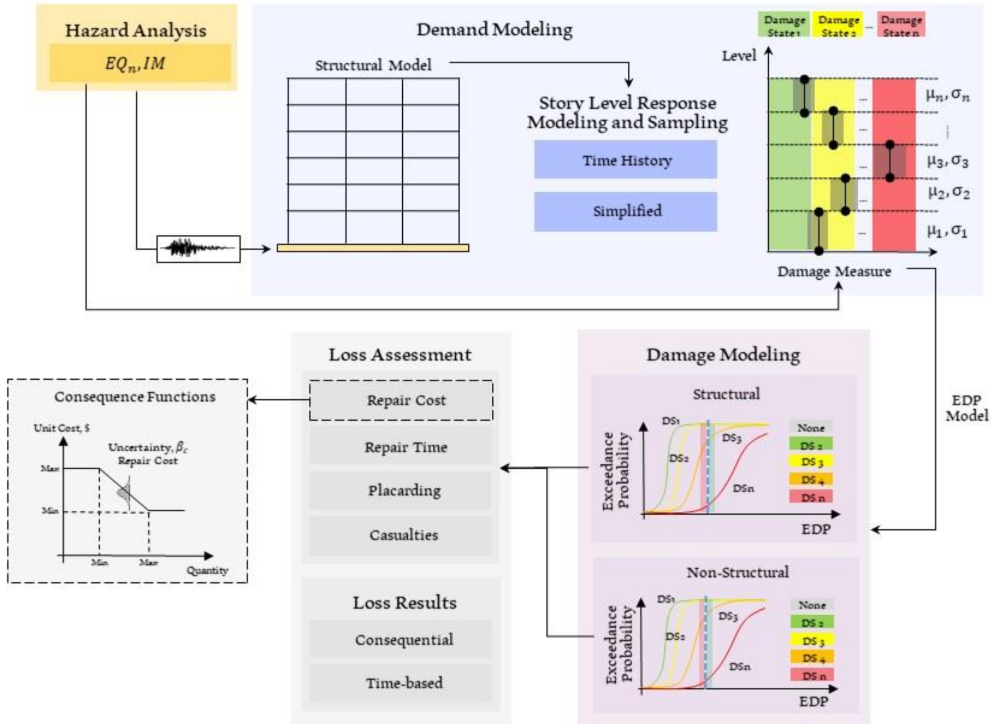


Figure 1. Summary of the proposed FEMA P-58 methodology for building-level loss assessment.

FEMA P-58 Methodology

FEMA P-58 [13] is a PBEE-compliant method for evaluating the seismic performance of individual buildings with a summary workflow as shown in Figure 1. A detailed understanding of the acceptable performance of buildings in earthquakes has been established over the many years during its development. To anticipate component-level damage states and their associated consequences, which are characterized in terms of repair costs, repair time, casualties, and building labeling, the methodology considers several steps with corresponding uncertainties. The implementation of the FEMA P-58 methodology starts with seismic hazard analysis. This step includes seismic hazard analysis for estimation of earthquake intensity measure (IM) which is used as input for damage measure (DM) estimation or directly used as input for seismic fragility functions. The second step includes response analysis to estimate DMs (e.g., Inter story drift). Afterward, in the third step, the estimated damage state from the previous step is used to map the DMs to their probability of being or exceeding a damaged state using fragility functions and performance groups. The fragility specification in FEMA P-58 is derived from incremental dynamic analysis (IDA) and considers the record-to-record uncertainty of hazard analysis and structural models. Finally, in the last step, the damage probabilities (i.e., IDA-based damage models) are converted to seismic loss measures based on consequence functions. Performance measures of a building subjected to an earthquake are established for different consequence functions such as repair cost, repair time, casualties, and unsafe placarding. The uncertainty associated with seismic performance prediction within this methodology is considered using sampling methods such as Mont Carlo (MC) sampling in different steps. Using the Total Probability Theorem, the PEER PBEE framework used as a basic equation for FEMA P-58 can be expressed as

$$p[DV|D] = \iiint p[DV|DM]p[DM|EDP]p[EDP|IM]p[IM|D]\, dIM.dEDP.dDM \quad (1)$$

where, the expression $p[X|Y]$ refers to the probability density of X conditioned on knowledge of Y; D denotes facility location, structural, non-structural, and other features; $p[IM|D]$ is the conditional probability of experiencing a given level of ground motion intensity given the location D; $p[EDP|IM]$ is the conditional probability of experiencing a level of structural response, given a level of ground motion intensity; $p[DM|EDP]$ is the conditional probability of experiencing the damage state, given a level of structural response; $p[DV|DM]$ is the conditional probability of experiencing a loss of a certain size, given a level of damage. The expected loss or value of the decision variable $p[DV]$ is calculated as the sum of these quantities.

PBM METHODOLOGY

The recently developed PBM methodology is achieved by simultaneously combining and advancing existing knowledge from structural mechanics, signal processing (i.e., nonlinear filtering), and performance-based earthquake engineering paradigms. The PBM can conduct building-level seismic damage and loss assessment which can be incorporated into regional loss and risk assessments. Using seismic response measurements and nonlinear M-DF, PBM can reconstruct various DMs. Additionally, fusion-based damage models are developed to estimate the probability of exceeding damage states based on performance-based criteria. The choice of damage states can also be optional and the users can adopt various limit states based on various damage-sensitive features that the methodology allows to select as a DM. PBM consists of four general steps including 1) measurement, 2) dynamic response reconstruction, 3) damage analysis, and 4) loss analysis. The outcome of every step of the proposed concept is characterized by one of four generalized variables, including response measurement (M), engineering demand parameter (EDP), damage measure (DM), and decision variable (DV). Using the Total Probability Theorem, the proposed framework equation is expressed by

$$p[DV] = \iiint p[DV|DM]p[DM|EDP]p[EDP|M]p[M]\, dM.dEDP.dDM \tag{2}$$

where $p[M]$ is the probability density of the measurement set, and $p[EDP|M]$ is the conditional probability of experiencing a level of the response given measurement set M. Except for a few special cases, solving the multidimensional integrals in Eq. (2) is a challenging task as it requires the complete probability distribution of the $p[EDP|M], p[DM|EDP]$, and $p[DV|EDP]$ to be estimated.

The PBM methodology starts with developing a non-linear structural model of an instrumented building and measuring its seismic response subject to strong ground motions. The global response of a typical multistory building structure subject to strong ground motions can be accurately characterized by

$$\mathbf{M}\ddot{q}(t) + \mathbf{C}_\zeta \dot{q}(t) + f_R(q(t), \dot{q}(t), z(t)) = \mathbf{M}\boldsymbol{b_1}\ddot{u_g}(t) + \boldsymbol{b_2}w(t) \tag{3}$$

where the vector $q(t) \in \mathbb{R}^n$ contains the relative displacement (with respect to the ground) of all stories. $z(t)$ is a vector of auxiliary variables dealing with material nonlinearity and damage behavior. n denotes the number of geometric degrees of freedom, $\mathbf{M} = \mathbf{M}^T \in \mathbb{R}^{n\times n}$ is the mass matrix, $\mathbf{C} = \mathbf{C}_\zeta{}^T \in \mathbb{R}^{n\times n}$ is the damping matrix, $f_R(\cdot)$ is the resultant global restoring force vector. The matrix $\mathbf{b_1} \in \mathbb{R}^{n\times r}$ is the influence matrix of the r ground acceleration time histories defined by the vector $\ddot{u_g}(t) \in \mathbb{R}^r$. The matrix $\mathbf{b_2} \in \mathbb{R}^{n\times p}$ defines the spatial distribution of the vector $w(t) \in \mathbb{R}^P$, which in the context of this paper represents the process noise generated by unmeasured excitations and (or) modeling errors. Additionally, the measurement process begins by determining the type, number, and locations of the sensors considering technical, logistical, and economic constraints. This paper focuses on accelerometers as the sensor of choice due to their popularity, durability, and reliability to reconstruct damage measures. In a typical setup, accelerations are measured horizontally in three independent and non-intersecting directions and the vector of acceleration measurements, $\ddot{y}(t) \in \mathbb{R}^m$, is given by

$$\ddot{y}(t) = -\boldsymbol{c_2}\mathbf{M^{-1}}\left[\mathbf{C}_\zeta \dot{q}(t) + f_R\big(q(t), \dot{q}(t), z(t)\big) - \boldsymbol{b_2}w(t)\right] + v(t) \tag{4}$$

where $\mathbf{c_2} \in \mathbb{R}^{m\times n}$ is a Boolean matrix that maps the degrees of freedom to the measurements, and $v(t) \in \mathbb{R}^{m\times 1}$ is the measurement noise. To determine the number and location of sensors (the measurement matrix $\mathbf{c_2}$ in Eq. (4)) an optimality criterion is needed. In this paper, the aim is to place accelerometers in locations that contain maximum information for response reconstruction, i.e., select the number and locations of sensors in a way that minimizes the uncertainty of response reconstruction. This minimization can be achieved by selecting an optimality criterion based on the variance of a user-defined objective function related to the estimated state of the system, such as displacement, internal forces, and stresses.

The response prediction performance of nonlinear structural models can be improved by incorporating sensor measurements. This approach deviates from model-driven approaches that update the model parameters, and instead, it performs nonlinear FE M-DF by feeding the sensor measurements as a corrective force applied to a modified FE model of the building. This enhanced model provides estimates of all relevant response quantities such as inter-story drift and element forces, with their corresponding uncertainty. The M-DF is implemented using a nonlinear model-based observer. The observer estimates the displacement response, $q(t)$, is given by the solution of the following equation (similar to Eq. (3)) by

$$\mathbf{M}\ddot{\hat{q}}(t) + (\mathbf{C}_\zeta + \mathbf{c}_2{}^T\mathbf{E}\mathbf{c}_2)\dot{\hat{q}}(t) + f_R(\hat{q}(t), \dot{\hat{q}}(t), z(t)) = \mathbf{c}_2{}^T\mathbf{E}\dot{y}(t) \tag{5}$$

where $\dot{y}(t)$ is the measured velocity and $\mathbf{E} \in \mathbb{R}^{m\times m}$ is the feedback gain. As can be seen, Eq. (5) is of the same form as the original nonlinear model of the building in Eq. (3). A physical interpretation of the non-linear model-based observer (NMBO) can be obtained by viewing the right-hand side of Eq. (3) as a set of corrective forces applied to a modified version of the original nonlinear model of interest in the left-hand side. The modification consists of adding the damping term $\mathbf{c_2}^T\mathbf{E}\mathbf{c_2}$, where the matrix $\mathbf{E}$ can be calculated using an optimization procedure outlined in [1] that requires using the linearized model of the building and power spectral densities of the measurement and process noise. The optimization problem is given by.

$$\begin{aligned} &\underset{\mathbf{E}}{\text{minimize}} \quad J = \text{tr}\,(\mathbf{P}) \\ &\text{subject to} \quad \mathbf{E} \in \mathbb{R}^{+}, \end{aligned} \tag{6}$$

where $\mathbf{P}$ is the displacement estimation error covariance matrix given by

$$\mathbf{P} = \mathbb{E}[(q(t) - \hat{q}(t))(q(t) - \hat{q}(t))^T] = \int_{-\infty}^{+\infty} \Phi_{ee}(\omega) d\omega \tag{7}$$

Since the objective is to estimate inter-story drifts, the objective function can be defined as follows:

$$J = \text{tr}(\mathbf{P}_{\text{Drift}}) = \sum_{i=1:N} \begin{cases} \mathbf{P}(1,1) & \text{for } k = 1 \\ \mathbf{P}(k,k) + \mathbf{P}(k-1,k-1) - 2\mathbf{P}(k,k-1) & \text{for } k \neq 1, \end{cases} \tag{8}$$

where k is the story number and N is the total number of stories. With this selection of the feedback matrix $\mathbf{E}$, the NMBO becomes a modified nonlinear model of the system with added grounded dampers obtained from a linearized model of the system at the measurement locations and excited by forces that are linear combinations of the measurements proportional to the added dampers.

Eq. (8) can be used to perform optimal placement by obtaining J values corresponding to various sensor placement scenarios and selecting the optimal measurement matrix, $(\mathbf{c}_2)_{\text{opt}}$, subject to PID estimation variance being bounded by a maximum allowable variance of σ^2_{max}, which can be specified based on the expected accuracy to determine the performance-based post-earthquake re-occupation category of the building of interest. This optimization problem can be formulated as follows

$$\begin{aligned} (\mathbf{c}_2)_{\text{opt}} = \quad &\underset{\mathbf{c}_2}{\arg\min} \text{tr}\,(\mathbf{P}_{\text{PID}}) \\ &\text{s.t. } \max[\sigma^2_{\text{PID}}(k,k)]_{k=1:n} < \sigma^2_{\text{max}} \end{aligned} \tag{9}$$

Once the building is instrumented on optimal locations and seismic measurements become available, the complete seismic response of the building can be obtained by solving Eq. (5) and used for component-level reconstruction of DMs of choice such as inter-story drifts. These DMs as reconstructed engineering demand parameters (REDP) can be used as input for fusion-based damage models as shown in Figure 2. Once REDP data are available, the fusion-based damage functions are developed based on the limit state criteria of choice to estimate the probability of being or exceeding a damage state. The probability of exceeding a specific performance level (PL) for a certain DM such as PID ratio, $p[DM_k \geq PL]$, can be calculated for each story as follows

$$p[DM_k \geq PL] = \int_{PL} p[DV_k|DM_k] dDM_k = \int_{PL} p(PID_k) dPISD_k = F_{PID}(PID_k \geq PL) \tag{10}$$

where $PISD_k \geq PL$ is the probability of PID_k exceeding specific performance levels (PL) at story k and F_{PID} is the cumulative probability density (CDF) of the estimated PID at story k. Conservatively assuming that the PIDs are independent, the probability of exceeding a specific performance level for a specific damage measure such as PID, $PID_k \geq PL$, for a building can be calculated as follows

$$p[DV_k|PL] = p[PID_k|PL] = 1 - \prod_{k=1}^{n} (1 - p[PID_k|PL]) \tag{11}$$

The last step of the PBM-based loss assessment methodology is to estimate loss measures from estimated damage state probabilities conditioned on DM given by $p[DV|DM]$. Once the $p[DS|DM]$ becomes available FEMA P-58 consequence function such as 1) repair cost, 2) repair time, 3) casualties, and 4) placarding as well as Hazus physical loss ratios can be convoluted to estimate losses. In contrast to FEMA P-58 with fully probabilistic consequence functions, Hazus adopts a different approach towards the conversion of damage state information to estimates of loss values. As a deterministic approach, with a broader consideration of building damage impacts that can be directly derived from building damage/loss, Hazus concentrates on cost consequences that are critical for crisis management and planning. Direct economic losses as a result of building damages within Hazus methodology are 1) building repair cost, 2) building content loss, and 3) building inventory loss. In addition, time-dependent consequences because of functionality disruption such as 1) relocation expenses, 2) income loss, 3) rental income loss, and 4) wage losses are also considered as direct physical economic losses for each building type and occupancy class for both structural and non-structural damages using inventory information and economic data.

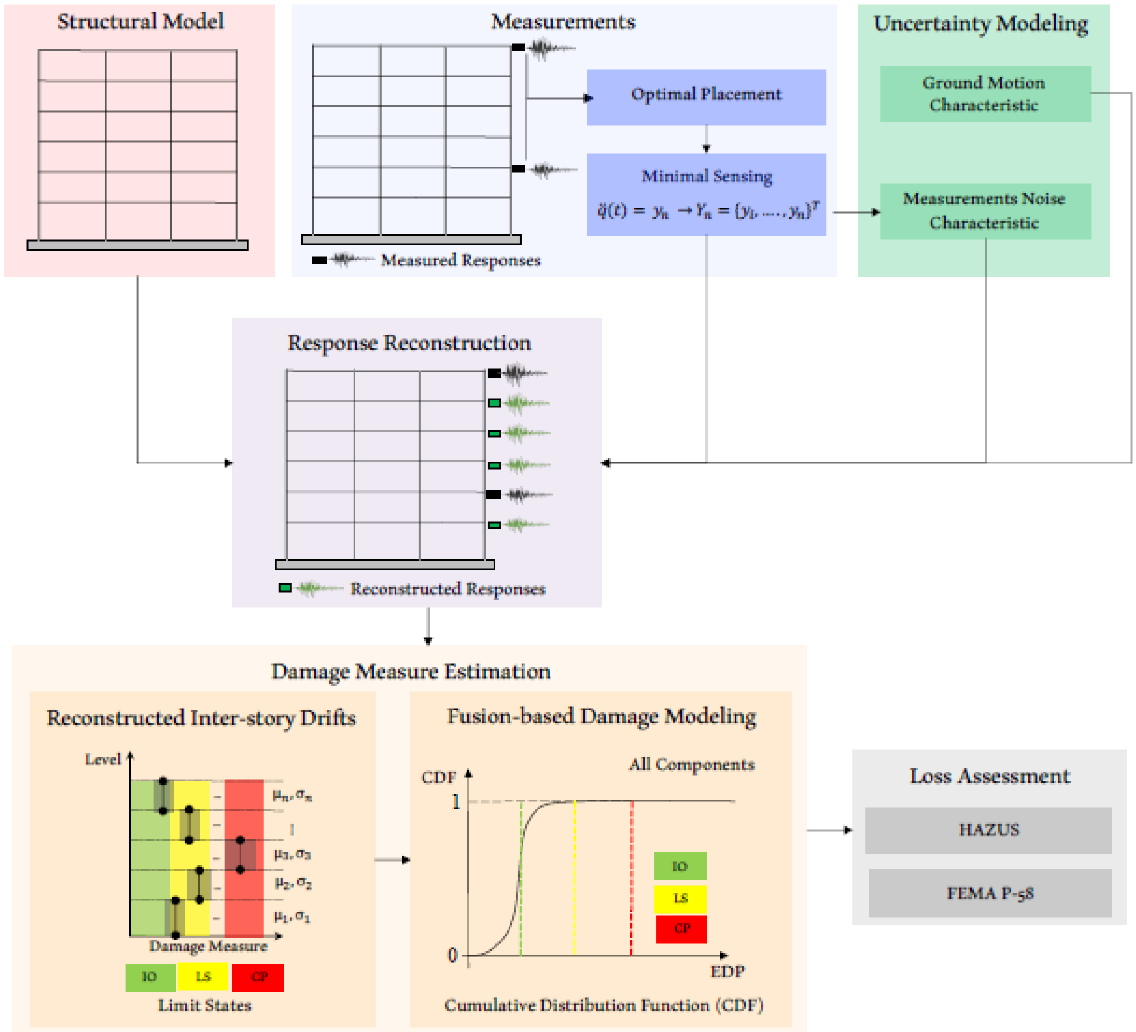


Figure 2. Summary of the proposed PBM-based methodology for building-level loss assessment.

With available damage state exceeding probabilities estimated using the PBM concept, different approaches toward the estimation of loss can be adopted using either the FEMA P-58 consequences function or Hazus loss ratios. The choice of each approach is optional and can depend on the objective of the loss assessment. For example, the FEMA P-58 approach can be implemented more efficiently when a detailed building-level assessment with careful evaluation of contents and non-structural components is required. The assessment results in this case can be used for building-level decision-making during immediate re-occupancy planning, recovery planning, and damage assessment. On the other hand, Hazus provides the baseline values for the structural loss consequences as deterministic ratios for each performance level and occupancy classification. Although Hazus offers a building-specific module for loss assessment, it is recommended to use it when the objective is to perform approximate loss assessment without the use of a detailed building asset model (e.g., the quantity of content and their specific characteristics). If needed, user-defined loss functions can also be adapted for case-specific loss assessment.

CASE STUDY OF NEESWOOD CAPSTONE 6-STORY WOOD FRAME BUILDING

This study is implemented on a six-story wood-frame Capstone building tested in a series of full-scale seismic tests in the final phase of the NEESWood project. The building was designed using a simplified direct displacement design (DDD). 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 3, instrumentation consisted of several gauge types ranging from 3D accelerometers to 3D optical tracking lights on the exterior of the building. Further details regarding instrumentation and measured response are as follows.

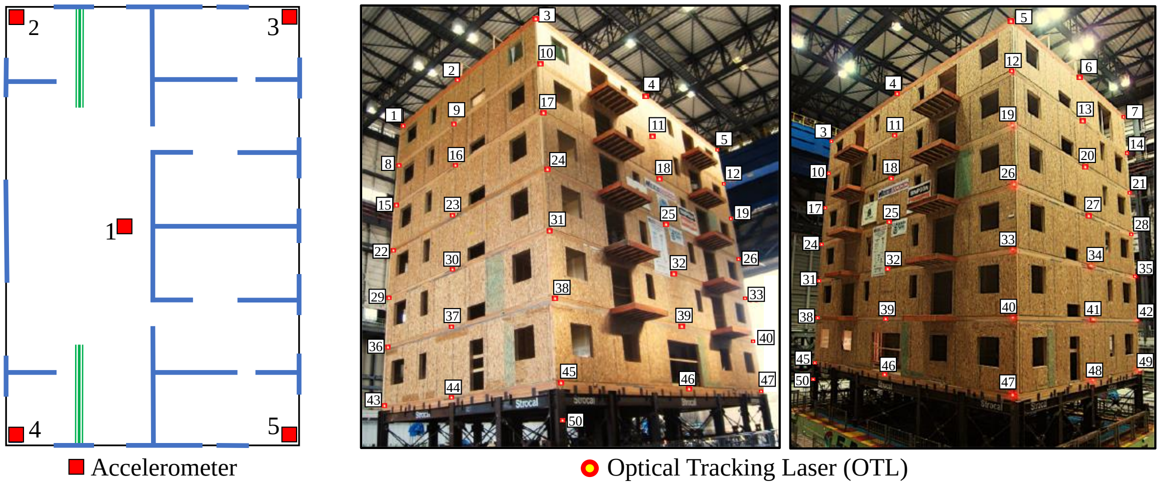
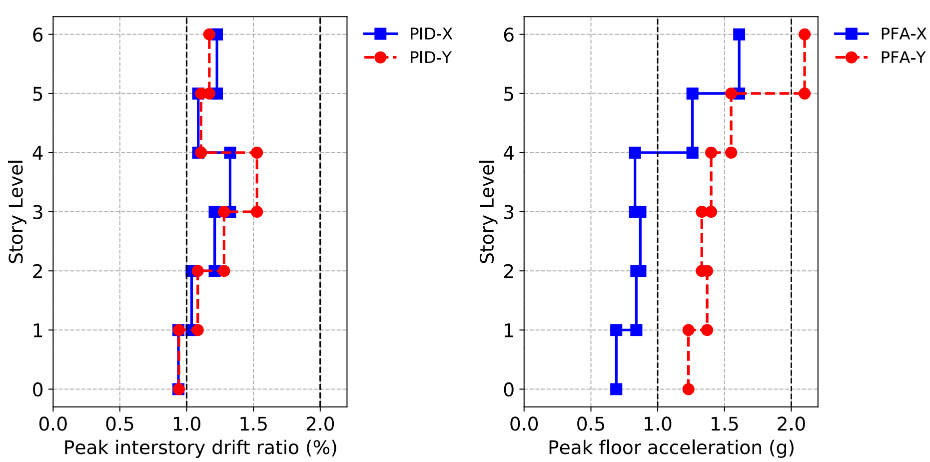


Figure 3. Schematic figure of NEESWood frame shake table test model.

The building was instrumented with over 300 channels consisting of acceleration, displacement, strain, and optical tracking measurements [14]. Different types of DMs can be used within damage models to the estimated probability of exceeding a damage state. DMs such as 1) story drift ratio, 2) damageable wall drift, 3) peak floor acceleration, 4) peak ground acceleration, 5) peak spectral acceleration or displacement, and so on can be either measured or simulated to estimate damage states probabilities within building-level loss assessment methodologies. The most common DMs, which demonstrated significant sensitivity for both structural and non-structural components are 1) PID ratio and 2) peak floor acceleration (PFA). The story-level recorded PID and PFAs for seismic test 5 in X and Y directions as an average of recorded responses in various locations for the structure are shown in Figure 4.

This study aims to explore loss estimation with direct measured EDPs and REDPs from the NMBO model through the PBM concept. To consider different sources of uncertainty (e.g., measurement uncertainty), the dispersion of recorded data based on a simplified analysis is adopted as a judgmental value in accordance with FEMA P-58 simplified analysis. The estimation of measurement dispersion allows a fully probabilistic analysis for different performance measures. In this study for the sake of simplification, the simplified estimation of dispersion as signal-to-noise ratio (SNR) of 20 (dispersion = 5%), and 50 (dispersion = 2%) for optical tracking sensors and accelerometers is added uniformly for all story levels to directly measured averaged EDPs (e.g., PID and PFA) for sampling purposes and uncertainty consideration within loss assessment methodologies.



(a) (b)

Figure 4. EDP data for the seismic test number 5: (a) PID, (b) PFA

NMBO Estimates of REDPs

In the verification step, a nonlinear 3D model of the building in OpenSees (verified with the M-SAWS model in [15]) is used as a surrogate model, and simulated data are generated by subjecting the model to the measured ground motion. The model includes every structural wall idealized as a pure shear element capable of resisting horizontal forces in its plane. The force-displacement relationship in each wall is modeled using the SAWS 10-parameter hysteretic model (refer to [15] for further details).

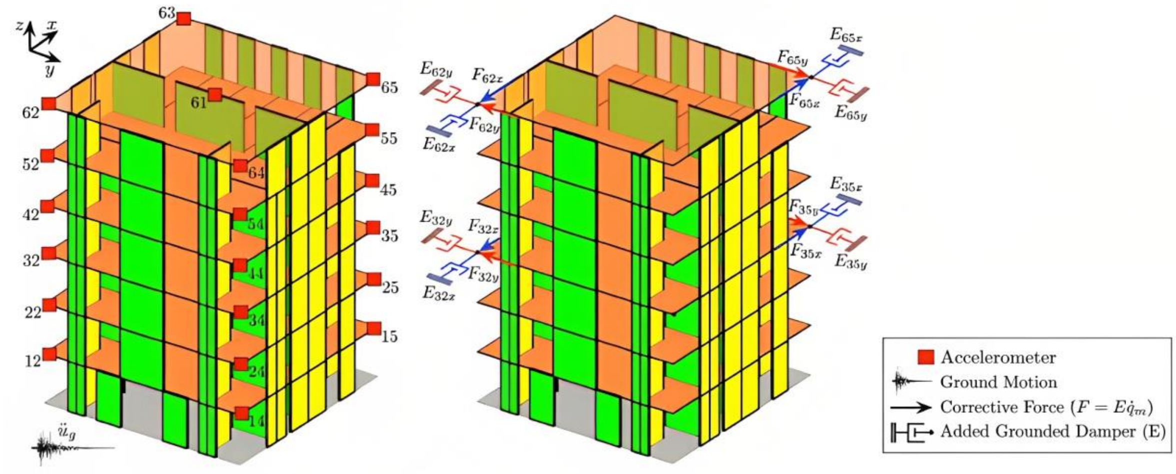
In this section, the application of NMBO for DM estimation using simulated response measurements is implemented. The proposed NMBO model is implemented using a nonlinear 3D model of the building in OpenSees with added grounded dampers at measured locations (Figure 5).

The observer estimates of building response and demands are compared for every story. Various measurement feedback scenarios were tested, and the results show that acceleration measurements at two floors (story three and roof with 3 measurements per floor) are enough to reconstruct the complete nonlinear dynamic response with high accuracy as set out In Table 1. Interested readers are referred to [1] for further information regarding the estimation of J as the objective function to determine the optimal level of instrumentation.

The proposed observer provides very good tracking capabilities in demand estimation including nodal displacements, inter-story drifts, and force-displacement hysteresis of shear walls using a relatively small number of measured seismic responses from the simulated building. Figure 6 shows the NMBO estimates of REDPs as estimated PIDs under the ground motion from the seismic test number 5. These results can be used as input EDPs for FEMA P-58 or Hazus loss modules.

Table 1. Estimated values for J objective function for different levels of instrumentation.

Number of Instrumented Floors	J	Direction	E					
			Floor 1	Floor 2	Floor 3	Floor 4	Floor 5	Floor 6
One	0.8324	X						6.3
		Y						61.66
Two	0.0194	X	1307.47					22.26
		Y	755.10					25.40
	0.0093	X		233.55				39.48
		Y		505.81				39.09
	0.009	X			163.16			55.54
		Y			307.77			94.32
	0.0211	X				158.37		99.70
		Y				307.77		95.82
Three	0.0069	X	81.95		153.44			53.04
		Y	699.78		224.99			81.17
Six	0.0043	X	44.42	48.24	59.67	103.51	183.89	147.11
		Y	209.62	215.23	227.13	80.66	103.08	50.59



(a) (b)

Figure 5. (a) Open-loop OpenSees model with the location of acceleration measurements from the shake table testing of the NEESWood building, (b) nonlinear model-based observer of the building implemented as a modified OpenSees model subject to corrective forces obtained from a limited number of measurements in optimal locations.

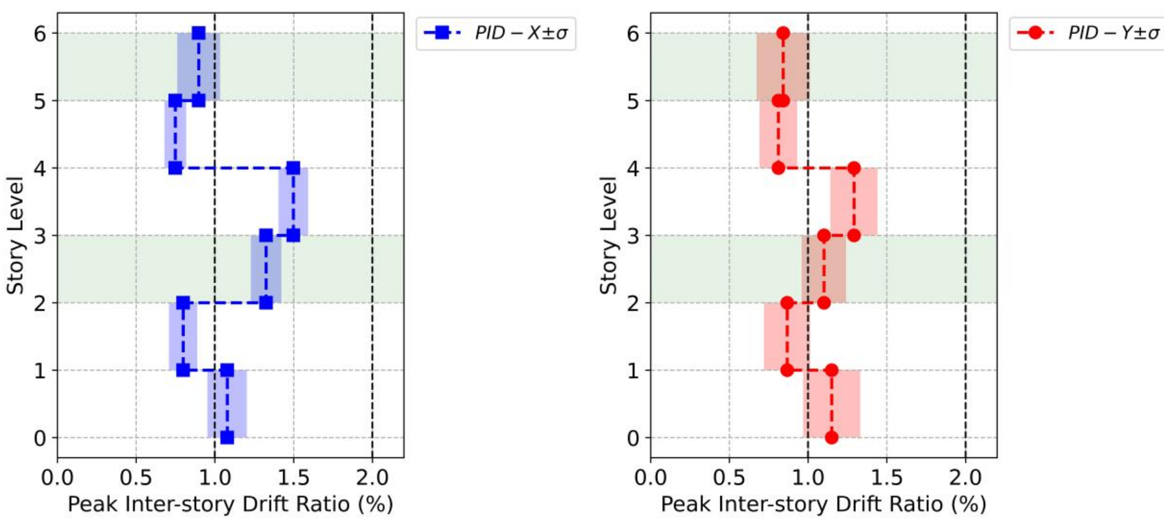


Figure 6. REDPs using two-level measurements on stories 3 and 6 for the seismic test number 5.

LOSS ESTIMATES RESULTS

In this section, loss estimates using direct EDPs and REDPs are compared. The performance-based engineering (PBE) software based on the Pelicun library is used to calculate loss values [16, 17]. This software allows the implementation of FEMA P-58 and Hazus methodologies separately and also it allows users to use their user-defined demand and fragility data. A light-wood frame structure with shear wall structural components with a residential occupancy class is considered for loss assessment. Specific consideration to implement loss assessment is discussed in the following.

FEMA P-58 Loss Estimates based on direct EDPs

The FEMA P-58 methodology begins with establishing the EDP model. Generally, FEMA P-58 uses two different approaches to develop demand models for performance assessment for single ground motion intensity or an earthquake scenario. In the first approach, users can develop demand sets using non-linear time history analysis to establish demand means and dispersion using multiple simulations. In another approach, called simplified analysis, users can run a single simulation with the judgmental determination of demand dispersion. Herein, the EDPs directly extracted from measurements as shown in Figure 4 are used for sampling using MC simulation to evaluate the uncertainty of performance outcome. This enables us to produce a probabilistic assessment of each seismic ground motion test. As shown in Figure 7, EDP sets are simulated for 500 realizations using MC sampling using a normal distribution. The demonstrated results are recordings from seismic test 5 for X direction of input ground motion.

Once the EDP model is established, the asset model with building basic data including the structural and non-structural assets and their quantities, plan area and the number of stories, and occupancy class is established. The building replacement cost for NEESWood light-wood frame (for 14,000 (ft^2)) is also calculated to be (109.66 (\$)$\times$14,000 (ft^2) = 1526000 (\$)) based on the Hazus Inventory Manual for the occupancy class of residential multi-family dwellings (RES3A-F).

Additional assumptions such as consideration of the thresholds for irreparability of damages in damage models, truncation of abnormal data in-demand model (e.g., estimated EDPs in non-linear states of the building using FE models), and the effects of residual drifts within FEMA P-58 methodologies can also influence the results. Therefore, in this research, the truncation limit for PID is considered as a drift ratio of 6%, and for PFA is story level acceleration of 2(g). Also, the yield drift ratio is 0.52% to calculate residual drifts based on the defined equation of FEMA P-58 to estimate irreparable damage and indicated total loss for elements [14]. The loss estimates, as shown in Figure 8 through a fully probabilistic process are calculated for three levels of ground motions (e.g., seismic tests 3 to 5).

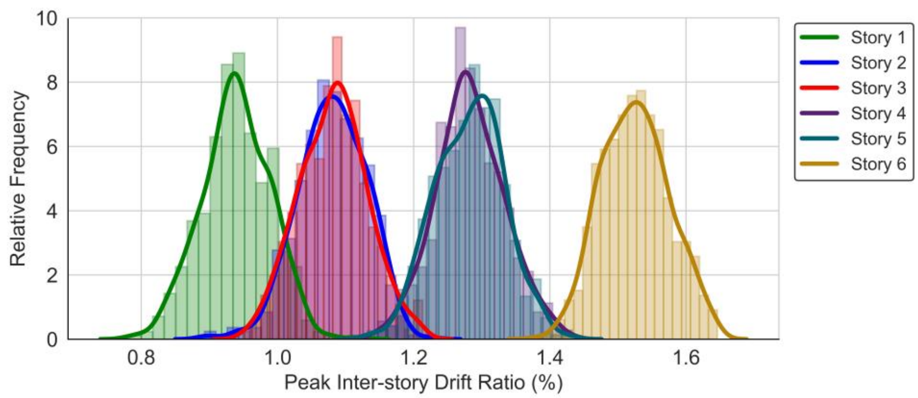


Figure 7. Simulated demand sets using MC sampling from direct PIDs for X direction of the seismic test number 5.

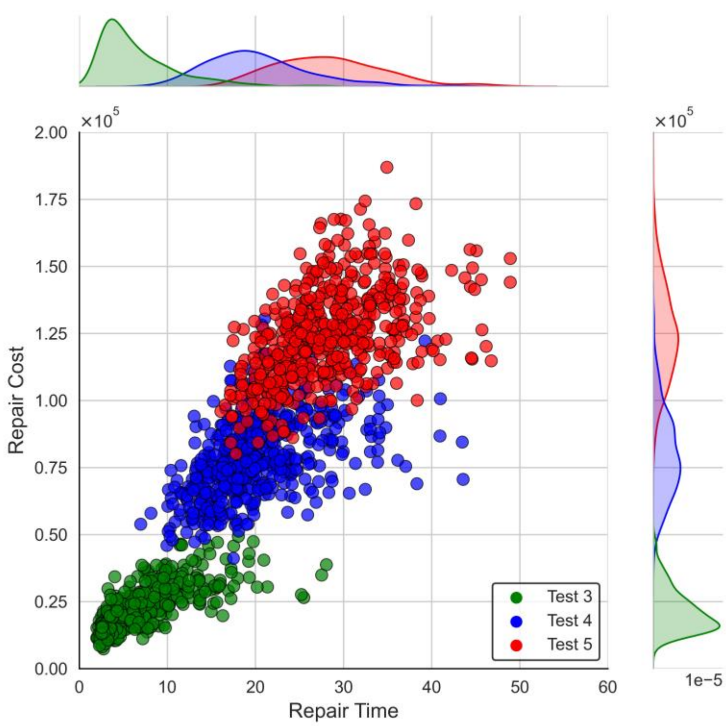


Figure 8. Repair time (parallel) and cost loss estimates using FEMA P-58 methodology from direct measured EDPs.

FEMA P-58 Loss Estimates based on REDPs

The loss estimates in this section are obtained only with a different EDP model (e.g., REDP model) using similar assumptions to the previous section for asset modeling and loss analysis. The results are shown in Figure 9. The EDP model is the reconstructed PID data from Figure 6. Also, direct measured PFA data are used in association with the REPD model because currently displacement data are only reconstructed using the NMBO model. As shown in Figure 10, the loss estimates obtained using directly measured EDPs from densely instrumented NEESWood building provide very close results compared to those obtained using the REDPs using a nonlinear M-DF with a limited number of sensors. These results demonstrate the effectiveness and cost-benefit of a minimal sensing and nonlinear M-DF approach for PBM and subsequent seismic loss assessment.

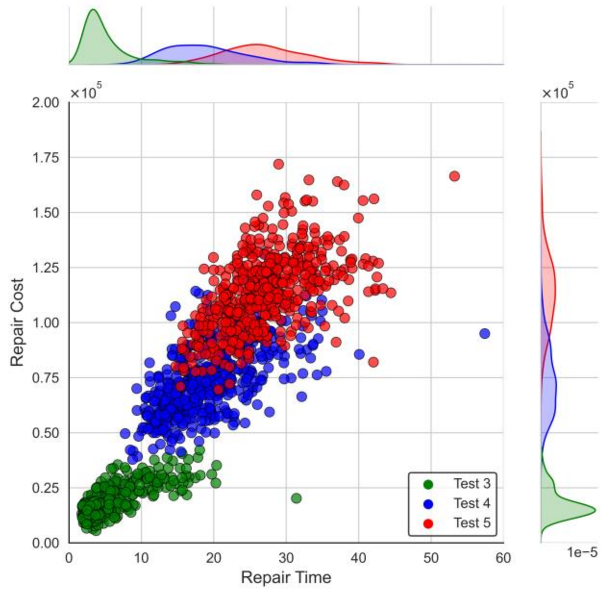
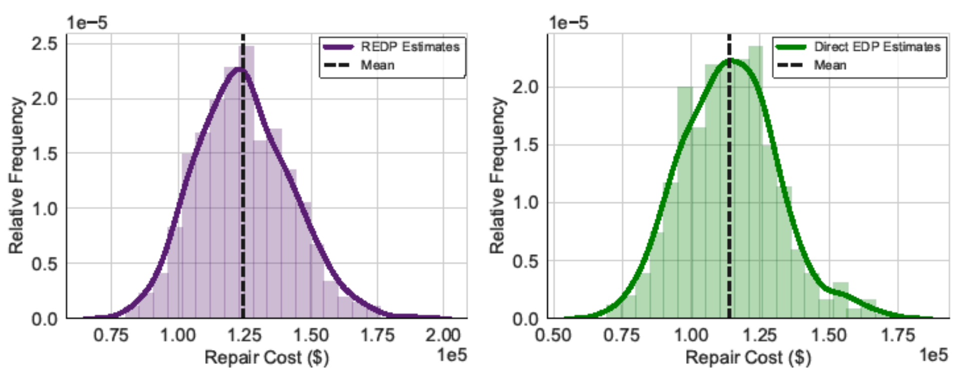


Figure 9. Repair time (parallel) and cost loss estimates using FEMA P-58 methodology from REDPs.



(a) (b)

Figure 10. The repair cost estimates using FEMA P-58 methodology: (a) NMBO REDPs, (b) directly measured EDPs for the seismic test number 5.

CONCLUSION

This paper implements a recently developed performance-based monitoring (PBM) concept to perform seismic loss assessment. The PBM includes four steps: 1) measurement, 2) dynamic response reconstruction, 3) damage analysis, and 4) loss analysis. It uses a nonlinear model-data fusion approach to combine a limited number of global response measurements (obtained from a structural monitoring system with accelerometers placed in optimal locations) with a nonlinear structural model to improve the prediction capability of the model. This approach allows for reconstructing the full nonlinear response of an instrumented building during an earthquake, which can be used to estimate the time history and dispersion of inter-story drifts. The probability and cumulative distribution functions of peak inter-story drifts (PIDs) are then used as fusion-based damage models to quantify the probability of exceeding various limit states consistent with performance-based earthquake engineering criteria. The outcome is used as input to loss estimation methodologies such as FEMA P-58 and Hazus to quantify the seismic loss.

The proposed approach is studied using real-world measured data from the extensively instrumented NEESWood Capstone building full-scale seismic tests conducted at the E-Defense facility in Japan. The loss estimates using reconstructed engineering demand parameters (REDPs) with a limited number of sensors provided very close results compared to those obtained using directly measured engineering demand parameters (EDPs) from the extensively instrumented NEESWood building. This highlights the effectiveness and cost-benefit of minimal sensing for PBM and subsequent seismic loss assessment.

This methodology can help engineers accurately estimate seismic damages and consequences for resilience-informed functionality assessment, as well as determine the performance and loss state of an instrumented building of interest for making decisions with specific attention to post-event re-occupancy planning. Future studies will focus on implementing loss assessment with fusion-based damage models within the PBM concept and evaluating different loss estimates for FEMA P-58 and Hazus consequence function and loss ratios.

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