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QUANTIFYING THE BENEFITS OF BUILDING INSTRUMENTS TO FEMA P-58 DAMAGE AND LOSS PREDICTIONS

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ABSTRACT

Seismic instrumentation in a building is used to accurately capture its response during an earthquake. This is helpful for building owners in their post-earthquake decision-making process as, according to the Performance-based Earthquake Engineering Framework, the response data measured should lead to enhanced predictions of the event's consequences for the building. This instrumentation can be costly however, so it is useful to know the extent to which varying levels of its implementation within a building affect the accuracy of these predictions. The purpose of this study is to develop a methodology for quantifying the errors in damage and loss consequence predictions from the FEMA P-58 Seismic Performance Assessment procedure, when different numbers of building instruments are used to capture the response of a building in a given event. We use responses measured on an instrumented building during the 1994 Northridge earthquake, and obtain consequence predictions via Performance-based Earthquake Engineering analyses using the FEMA P-58 methodology. The density of instrumentation examined ranges from the case in which all floors are instrumented to that in which no instrumentation is present and FEMA P-58 simplified procedures are used to predict response and corresponding consequences.

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Seismic instrumentation in a building is used to accurately capture its response during an earthquake. This is helpful for building owners in their post-earthquake decision-making process as, according to the Performance-based Earthquake Engineering Framework, the response data measured should lead to enhanced predictions of the event's consequences for the building. This instrumentation can be costly however, so it is useful to know the extent to which varying levels of its implementation within a building affect the accuracy of these predictions. The purpose of this study is to develop a methodology for quantifying the errors in damage and loss consequence predictions from the FEMA P-58 Seismic Performance Assessment procedure, when different numbers of building instruments are used to capture the response of a building in a given event. We use responses measured on an instrumented building during the 1994 Northridge earthquake, and obtain consequence predictions via Performance-based Earthquake Engineering analyses using the FEMA P-58 methodology. The density of instrumentation examined ranges from the case in which all floors are instrumented to that in which no instrumentation is present and FEMA P-58 simplified procedures are used to predict response and corresponding consequences.

Introduction

In this study, we develop a methodology for quantifying the effect of building instrumentation on the accuracy of damage and loss consequence predictions from the FEMA P-58 Seismic Performance Assessment procedure [1]. These predictions can facilitate the post-earthquake decision-making of building owners [1]. For example, they can be used to rapidly evaluate whether a building can be re-occupied. It is important to quantify the level of building instrumentation required for accurate consequence predictions, since one of the main limitations of building instrumentation is its large capital cost.

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Seismic Instrumentation and Performance-based Earthquake Engineering (PBEE)

Let N be the number of floors (including roof) in a structure and n the number of floors with instrumentation. Possible instrumentation density in the structure can be divided into 3 categories: 1) No Instrumentation ($n=0$), 2) Partial Instrumentation ($0 < n < N$), and 3) Full Instrumentation ($n=N$). The effect of a given density of seismic instrumentation on the PBEE Framework depends on which of these 3 categories it belongs to.

When $n=0$, neither the ground motion intensity nor the structural response are measured for the structure in a seismic event. In this case, the PBEE Framework can be expressed as follows:

$$p(DV) = \iiint p(DV|DM)p(DM|EDP)p(EDP|IM)p(IM) dDM dEDP dIM \quad (1)$$

where IM (Intensity Measure) is the ground motion intensity measure, EDP (Engineering Demand Parameter) is the structural response, DM (Damage Measure) is the component-level damage, DV (Decision Variable) is the building loss, and $p(\cdot)$ is the probability of occurrence. Note that this is simply the classic PBEE Framework [2].

When $0 < n < N$, we assume there is at least ground floor instrumentation in the structure, which eliminates uncertainty on the ground motion intensity for a seismic event and therefore the IM integral from Eq. 1. The level of uncertainty in the structural response depends on the number of floors instrumented. When $n=N$, both the ground motion intensity and the structural response are measured. This eliminates the IM and EDP integrals from Eq. 1.

By decreasing the number of integrals to be evaluated, seismic instrumentation should increase the accuracy of consequence predictions. This hypothesis forms the basis of our methodology.

Outline of Methodology

We examine a building of interest subjected to a given seismic event. The building has N floors, n of which are instrumented. We systematically increase the level of instrumentation present, from $n=0$ to $n=N$. We investigate the effect of the structural response predictions resulting from each level of instrumentation on the accuracy of the building's damage and loss predictions for the event from the FEMA P-58 methodology. Predictions for the fully instrumented case ($n=N$) are taken as the benchmark. If the building of interest does not contain instruments on all floors, we assume the true responses at non-instrumented floors can be recovered using cubic spline interpolation [e.g. 3]. We use the SP3 software tool (www.hbrisk.com) to run the analyses.

The level of instrumentation present is reflected in the calculations via the uncertainties applied to the structural response inputs of the P-58 methodology (Table 1). Uncertainties are applied to responses at all floors for $n \leq 1$ (in line with the FEMA P-58 simplified procedure, which is used in these cases), and responses at least partially constrained by non-instrumented data for $n > 1$.

Table 1. Uncertainties in structural response inputs to the P-58 analysis for different n.

Level of Instrumentation	Structural Response Uncertainty
n=0	$\beta_a, \beta_u, \beta_{gm}$
n=1	β_a, β_u
$1 < n < N$	β_a, β_u
n=N	0

β_a represents aleatory uncertainty that varies for different values of n, β_u is a user-defined epistemic uncertainty, and β_{gm} is a ground motion uncertainty obtained from the ground motion model used.

The damage or loss prediction of interest is calculated according to the P-58 methodology for each arrangement of instrumentation at each value of n. An error metric is used to quantify the error in the prediction relative to the corresponding prediction calculated for the benchmark case.

Application

The methodology is applied to the 7-story Van Nuys hotel building [e.g. 4,5] and its response to the M_w 6.7 1994 Northridge earthquake. We examine the error in the P-58 prediction of building repair cost as a percentage of building value for different values of n.

Let \hat{L} denote the vector of P-58 repair cost percentage predictions for a given arrangement of instrumentation at a given value of n. Fig. 1a provides histograms of \hat{L} at each value of n, when $\beta_u = 0.5$. We use the following error metric to benchmark \hat{L} :

$$\text{Error} = \sqrt{\frac{\sum_{j=1}^{n_s} (\bar{L} - \hat{L}_j)^2}{n_s}} \quad (2)$$

where \bar{L} is the mean value of \hat{L} for n=N and n_s is the number of P-58 Monte Carlo samples. Fig. 1a indicates that there is an overall decrease in repair cost percentage prediction error as the number of instruments in the building is increased.

Fig. 1b provides a summary of the error in repair cost percentage prediction for each value of n, and different values of β_u . The error value plotted for a given value of n is the minimum across all arrangements of instrumentation for that value of n. We see that the error in repair cost percentage prediction generally decreases as n increases and the errors associated with $n \leq 1$ are notably larger than those for any other value of n, across all values of β_u examined. Note that this trend can be sensitive to the arrangement of instrumentation for a given value of n.

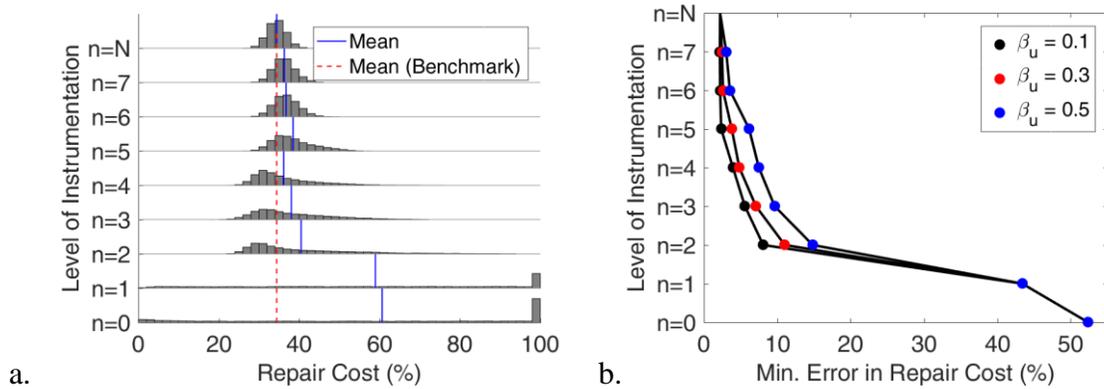


Figure 1. a. Histograms of P-58 repair cost predictions (as a percentage of building value) for different n , when $\beta_u = 0.5$. b. Minimum error in P-58 repair cost percentage prediction for different n , and various β_u .

Conclusions

This study provides a method for quantifying the effect of building instrumentation on the accuracy of damage and loss consequence predictions calculated from the FEMA P-58 Seismic Performance Assessment procedure. We have demonstrated the methodology by applying it to a 7-story structure for a given seismic event. The errors in consequence predictions decrease as the number of building instruments is increased, and the reduction in error is substantial as soon as more than only the ground floor is instrumented. This suggests that it may not be crucial to have a high density of instrumentation to obtain reasonable accuracy in FEMA P-58 consequence predictions, but the accuracy achieved for a chosen level of instrumentation may be dependent on the arrangement of instruments within the building. The above approach should provide actionable information for a building owner if they wish to use seismic instrumentation as a means of rapidly obtaining damage and loss information for post-earthquake decision-making.

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