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Fragility reduction using passive response modification in a Consequence-Based Engineering (CBE) framework

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Abstract. Consequence-Based Engineering (CBE) is a new paradigm proposed by the Mid-America Earthquake Center (MAE) to guide evaluation and rehabilitation of building structures and networks in areas of low probability - high consequence earthquakes such as the central region of the U.S. The principal objective of CBE is to minimize consequences by prescribing appropriate intervention procedures for a broad range of structures and systems, in consultation with key decision makers. One possible intervention option for rehabilitating unreinforced masonry (URM) buildings, widely used for essential facilities in Mid-America, is passive energy dissipation (PED). After the CBE process is described, its application in the rehabilitation of vulnerable URM building construction in Mid-America is illustrated through the use of PED devices attached to flexible timber floor diaphragms. It is shown that PED's can be applied to URM buildings in situations where floor diaphragm flexibility can be controlled to reduce both out-of-plane and in-plane wall responses and damage. Reductions as high as 48% in roof displacement and acceleration can be achieved as demonstrated in studies reported below.

Key words: consequence-based engineering; risk assessment; fragility reduction; response modification; passive energy dissipation; multi-criteria decision making; parametric analysis; meta-modeling.

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1. Introduction

Consequence-based Engineering is a process for seismic risk reduction across regions or systems that incorporates identification of the uncertainties in all components of risk modeling, and quantifies the risk to societal systems and subsystems (Abrams 2002). The steps for a CBE analysis are illustrated in the flowchart of Fig. 1. This process is executed by working with decision-makers to develop and assess risk reduction strategies. CBE is structured as a sequence of analyses and decisions that identify what consequences are possible from a probable hazard, and the impact of specific mitigation actions on reducing these consequences across a system of interest.

Initially a rapid assessment is performed to define the relevant system, approximate the probable hazard, estimate what consequences are likely, and identify what types of consequences might be acceptable.

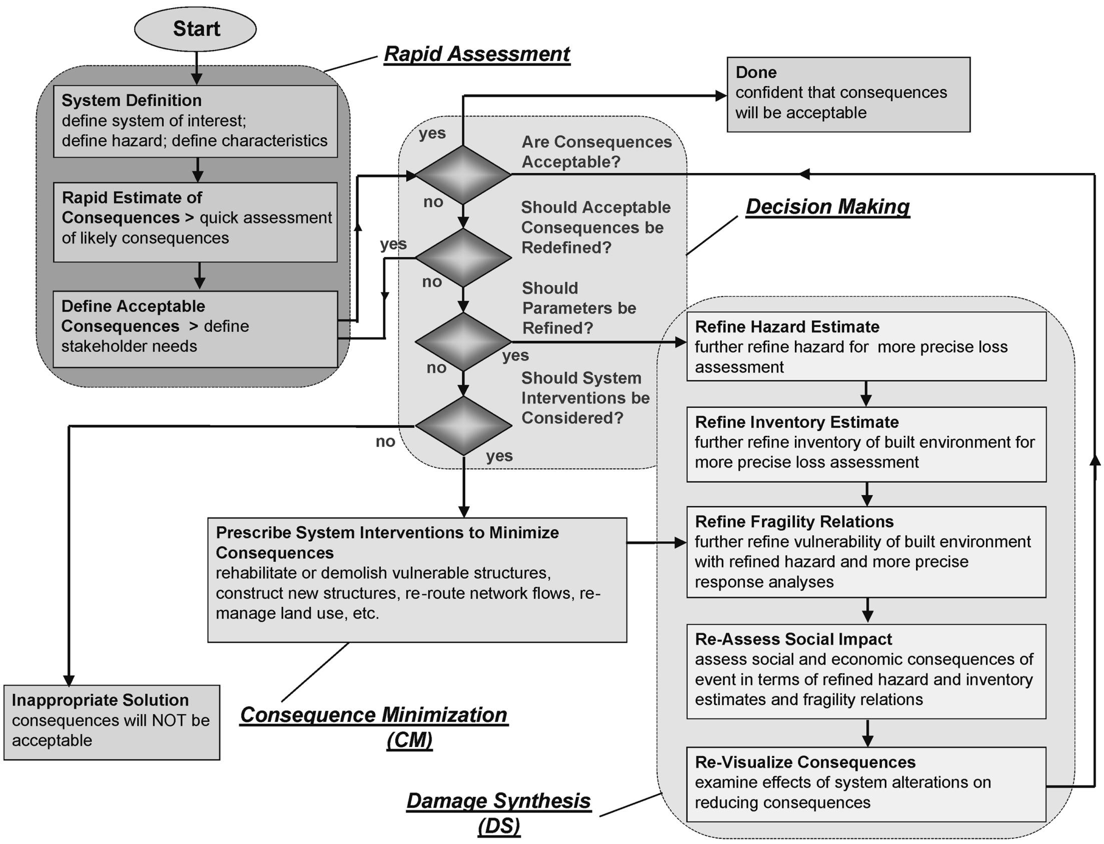


Fig. 1 Flowchart for Consequence-Based Engineering (CBE)

Next a four-step decision tree is used to determine: (a) if estimated consequences are acceptable, (b) if acceptable consequences should be redefined, (c) if modeling parameters should be refined, and (d) if further system interventions should be considered. If anticipated consequences are unacceptable, and no further redefinition of acceptability is feasible, then parameters defining the hazard and built environment must be refined to more accurately estimate anticipated losses (assuming that the preliminary analyses were conservative), and system interventions must be prescribed to minimize anticipated losses. An interactive damage synthesis module developed with advanced data mining and visualization tools is used to determine and view consequences for various problem definitions and mitigation scenarios. Using this module iteratively, consequences can be estimated for a number of different system intervention strategies using various input parameters describing the hazard, the built environment, and the values the decision maker is maximizing or trading off.

2. Consequence-based engineering implementation

This study examines the use of intervention strategies within the CBE paradigm for response modification of essential facilities in the Mid-America region. Essential facilities are defined as buildings that support functions related to post-earthquake emergency response and disaster management. For such buildings, simply ensuring life safety and preventing collapse does not constitute adequate or acceptable performance, since they must remain operational and suitable for immediate occupancy after a major earthquake. A regional inventory of essential facilities in Mid-America revealed that unreinforced masonry (URM) is the most common type of construction for these facilities (French 2000). Such material is well known to be vulnerable to even moderate earthquakes. One possible intervention strategy is response modification, which this study illustrates for the case of low-rise firehouses.

2.1 Earthquake vulnerability assessment

The damage synthesis process shown at the right in Fig. 1 is indispensable for either providing the reference data in carrying out a rapid assessment, or for refining model parameters to more accurately estimate losses. In both cases the methodology is the same; only the level of detail of the input variables varies. The procedure is implemented in a set of projects (MAE, 2002) which will refine the CBE process; the fundamental steps in CBE can be described as follows:

Definition of site specific earthquake ground motions: create and validate a geological, geotechnical and seismological database to characterize the Mid-America region (or other region of interest), and provide a reliable estimate of the potential hazard to be used in the decision making and consequence minimization processes. The results of this step are synthetic time histories; uniform hazard ground motions such as the ones developed for Mid-America cities (Wen 2001); site amplification factors; and attenuation relationships.

Parametric analysis on frequent typologies: from the inventory of structures and geostructures across a region, it is possible to represent the built environment using key parameters (geometric, structural and functional), and provide the basis for the definition of prototype structures and geostructures, Fig. 2. In this study the prototype structure corresponds to low-rise unreinforced masonry buildings used as firehouses. This category is one of a broader set of 36 building structure types and 28 occupancy classes consistent with known categories defined by FEMA (1997).

Statistical and probabilistic models of the structures: Sensitivity analysis and screening identifies the parameters that have the greatest influence on the response of the structures, Fig. 3(a). An experiment is designed to define the coefficients of the polynomial that represents the finite element model of the structure(s) of interest, Fig. 3(b). Structural performance is represented in the form of response surface equations (RSE), Fig. 3(c), which relate the input hazard with selected response quantities such as drift (chosen for this study), base shear or overturning moment. Finally, Monte Carlo simulations using the RSE's are used to obtain fragility curves on a macroscale, Fig. 3(d).

Definition of damage scenarios: A spatial distribution of the damage is depicted to provide a crucial input to the dynamic decision structure, in which decision attributes and objectives may vary over time as the decision maker iterates through identification of acceptable consequences, parametric analyses and proposed interventions.

2.2 Dynamic decision making

Following an estimation of the damage scenarios, CBE provides the decision maker with tools to determine what kinds of actions will reduce losses. Usually there are a number of candidates for intervention, including multiple schemes for rebuilding and for rehabilitation, or simply leaving the system as it is. The selection of the loss minimization or system intervention method among these options has to be made with caution because the selection is likely to require tradeoffs between different objectives (e.g., minimization of economic costs or construction time, maximization of life safety or building functionality). These values and risk preferences will vary both among decision makers and across decision contexts. In some cases, more than one decision maker will be involved, which means that there may be conflicting acceptability criteria for the same objective.

The first step of the decision analysis in CBE is to identify the attributes of the system that the decision maker values. As stated above, the decision maker may value monetary cost, building functionality, life safety, aesthetics, time-to-completion of an intervention, and other characteristics of the system or intervention. The next step is to evaluate the current system to determine if performance is acceptable or not based on the damage scenario produced in the earthquake vulnerability assessment. In CBE, the evaluation is for structural systems over a predetermined region during and after seismic events, and taking into account the impact, within the region or part of it, of network or geostructure loss of functionality.

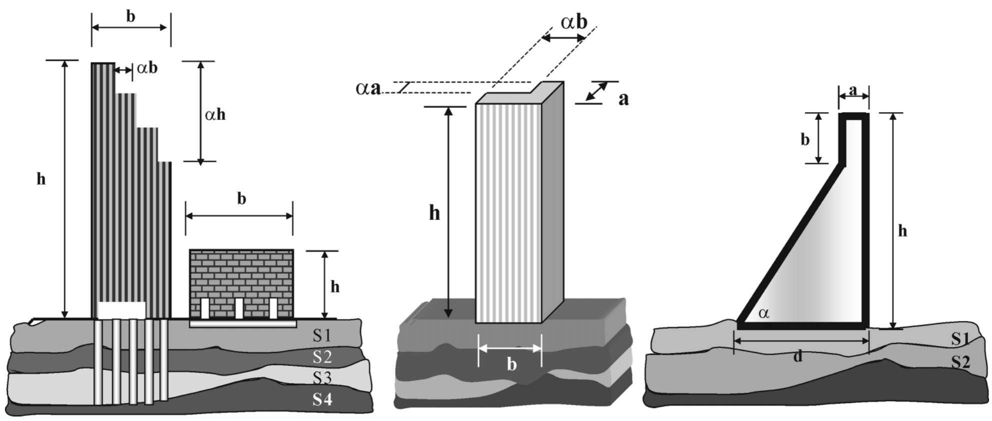
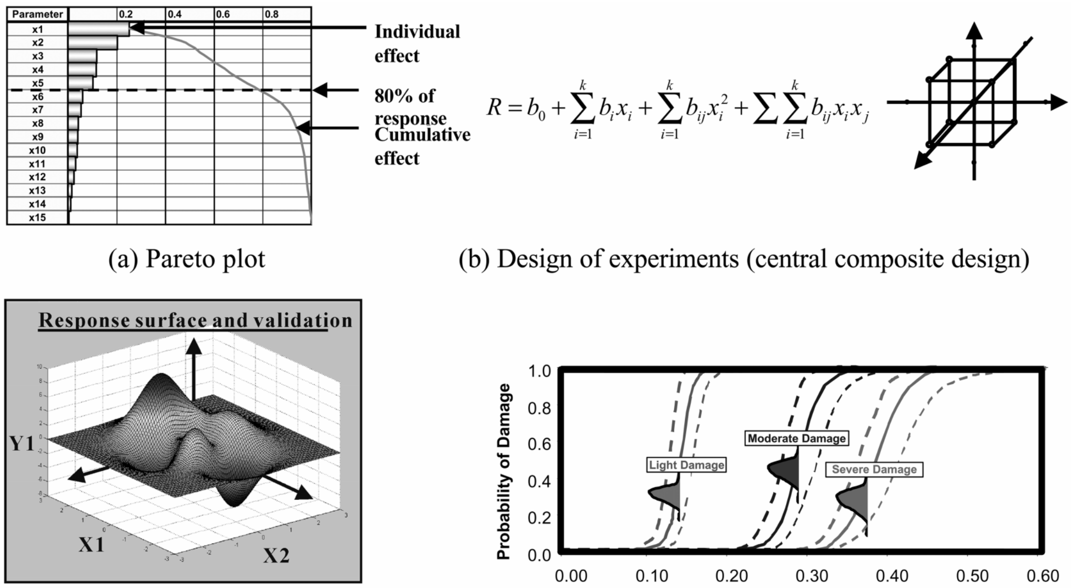


Fig. 2 Parametric analysis on frequent typologies



(a) Pareto plot

(b) Design of experiments (central composite design)

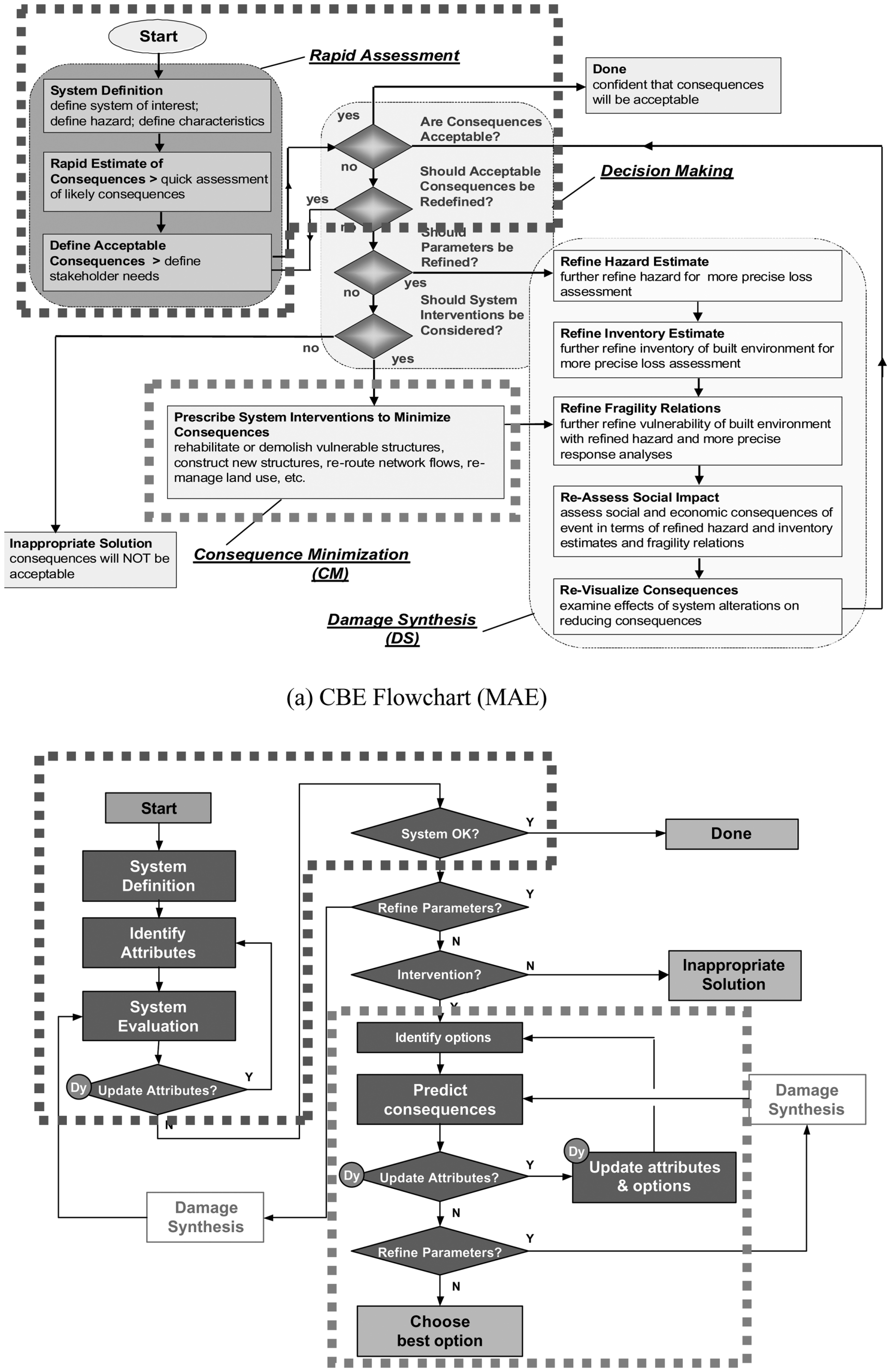
(c) Response surface

(d) Fragility curves

Fig. 3 Statistical and probabilistic models of the structures

If the anticipated consequences on the current system obtained from the initial analysis methods are not acceptable to the decision maker, a set of the available intervention options (alternatives), from which the decision maker can eventually choose, is presented to the decision maker. Each alternative system is then evaluated, producing corresponding anticipated consequences. Even if a unified decision maker is assumed, which is the case in this study, the level of consequences considered acceptable may depend on the value elicitation and problem representation. Decisions are usually made dynamically, by iteratively assessing values and alternatives (Corner *et al.* 2001). That is, when a set of alternatives is assessed, this process is likely to affect the decision maker's values, eventually producing an updated set of alternatives. Fig. 4(b) shows a modified decision flowchart, which emphasizes the dynamic characteristics of system intervention decision processes. Fig. 4(a) highlights the steps of the CBE process that are enhanced with dynamic decision making.

Since the values pertaining to earthquake mitigation often conflict each other, decision making tools that can handle more than one value, or multi-criteria decision making (MCDM) tools, have to be considered for the selection of the most effective intervention method. In addition, attempts to take into account the correlation among attributes have to be made. Maximum expected utility theory is a MCDM method widely used in the decision analysis field (Ang and Tang 1984, Winterfeldt and Edwards 1986, Hiller and Lieberman 2001). In this method, each of the decision maker's values is measured and expressed by a utility function, and a multi-attribute utility function is generated to integrate across values, accounting for the unique weight that is assigned to each value. Uncertainty is expressed probabilistically and incorporated to produce an expected value for each alternative. Among a set of available alternatives, the alternative with the highest expected utility is a likely candidate for selection. Another MCDM method that can be used in CBE is joint probability decision making (JPDM), in which the probability that a system will result in a target level of consequence is calculated (Bandte 2000).



(a) CBE Flowchart (MAE)

(b) Dynamic decision structure

Fig. 4 Parallel between CBE flowchart and dynamic decision structure

Intervention decisions to minimize anticipated losses from seismic events can be made with the aid of the decision analysis tools described above. In the case of the low-rise firehouses, the dynamic decision process brings into consideration feasible rehabilitation options for strengthening and response modification.

3. Rehabilitation options

Rehabilitation objectives for one- and two-story unreinforced masonry (URM) buildings typical of firehouses and police stations may include a combination of both strengthening to address major structural weaknesses (increase seismic capacity) and response modification to reduce seismic demand. Other likely objectives are minimizing the costs associated with rehabilitation and post-earthquake repairs. For purposes of illustration, we assume in this paper that applying passive energy dissipation devices is selected as the best option for the rehabilitation of low-rise URM structures, after taking into account other criteria (e.g., cost), optimizing the rehabilitation options (e.g., PED's) to maximize building performance and minimize cost, and evaluating the relative importance of each criterion, iteratively.

Normally, passive response modification is not considered for URM structures due to their very stiff characteristics with relatively little deformation available to activate typical passive energy dissipators (PED's). However, response modification can be achieved using simple PED's because the typical timber diaphragms are flexible enough to activate these devices. Preliminary research described here has shown that this can be an effective means of seismic response modification for certain kinds of low-rise URM buildings in the Mid-America region. Specifically, for one or two story structures with flexible floor and roof diaphragms and with fairly regular floor plans, the application of PED's can significantly reduce displacement responses in a reference building model.

3.1 Reference URM building

For the present work, the reference building is the full-scale URM building designed for a series of laboratory tests (Yi 2002). This structure is a two-story URM structure with a 24 ft by 24 ft plan and perforations in all four walls. One pair of opposing walls has symmetric openings to provide one axis of symmetry for the structure while the other pair of walls has widely different openings to create a strong asymmetry in the orthogonal direction. Floor and roof diaphragms as well as the masonry are designed to replicate properties typical of the majority of essential facility structures in Mid-America (built prior to the mid 20th century).

3.2 Rehabilitation schemes

A key characteristic of earthquakes in this region is the long-recurrence interval. Metallic hysteretic PED's are attractive for seismic protection systems under these conditions because they offer good long-term reliability, modest cost and relatively simple design. The PED considered in this study is a simple ductile metal flexural device based on designs studied in previous work (Pinelli 1996), but the results extend readily to other metallic hysteretic designs. Previous studies by the research team and others show that such devices, even those fabricated from mild steel, are

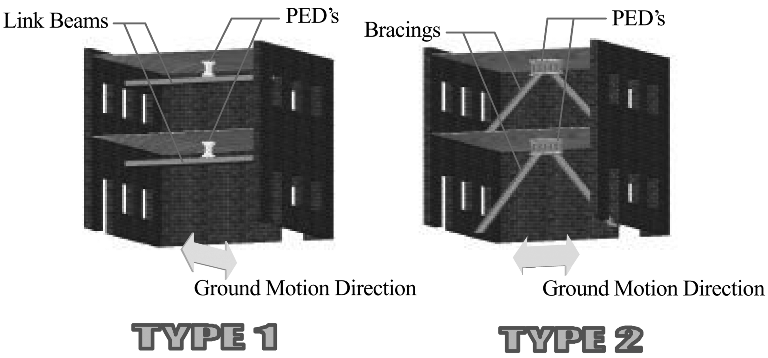


Fig. 5 Conceptual PED's using diaphragm flexibility

capable of developing large and stable hysteresis loops under cyclic loads and are capable of providing good and predictable energy dissipation (Moor 1992).

The devices considered in this study are activated using the flexibility in the floor diaphragm. One configuration makes use of relative displacement between a flexible floor diaphragm and the in-plane walls. Another potential configuration utilizes the relative displacement between the center of the flexible diaphragm and the ground. These implementations are called Type 1 and Type 2 rehabilitation schemes, respectively, as shown in Fig. 5. The Type 1 rehabilitation scheme can be implemented in a building by inserting a beam between two walls at opposite edges of a wooden diaphragm. If this beam is stiff enough, the lateral movement at its midspan will approximately equal the average of the in-plane movement of the supporting walls. Tapered metallic PED devices can be attached between the midspan of the beam and the center of the floor or roof diaphragm above. The PED will deform into the inelastic range as the wall and diaphragm move differentially. In the Type 2 rehabilitation scheme, the tapered PED devices are connected between the center of the diaphragm and the ground through a stiff Chevron or K-brace. Furthermore detailed explanation about the behavior of these rehabilitation schemes can be found in Craig *et al*. (2002).

The PED's are designed using an energy-based formulation derived from earlier research (Goodno 1998, Pinelli 1996, Craig 2002). In this approach, the "best" design for the PED is defined as the design that maximizes the ratio of energy dissipated in the PED (or PED's if multiple devices are used) to the total input seismic energy.

3.3 Response modification of reference URM building

A DRAIN-2dx design model was developed to capture the behavior of the reference building. The model was constructed using the DRAIN TYPE 04 zero-length nonlinear spring following the approach described in (Park 2002). The result is a one-dimensional (1D) model of zero-length springs connected between a number of coincident nodes. Table 1 presents the maximum displacements at the top of in-plane walls (IPW), out-of-plane (OPW) walls, and the diaphragm (DIA), resulting from a reference Carbondale ground motion (Wen 2001). It can be seen that reductions as high as 48% in the maximum displacement can be obtained when an appropriate passive rehabilitation system is applied.

Table 1 Comparison in maximum displacements

Location	Max Displacement (mm) Type 1 PED		% Reduction	Max Displacement (mm) Type 2 PED		% Reduction
	Existing	Rehabilitated		Existing	Rehabilitated	
Top of IPW	0.74	0.69	8	0.74	0.74	0
Top of OPW	11.51	7.57	34	11.51	7.11	38
Center of DIA	10.34	6.27	39	10.34	5.33	48

3.4 Fragility reduction

Since randomness and uncertainties are inherent in the problem, a single deterministic analysis is an insufficient means to evaluate a rehabilitation approach for an entire class of structures. Performance for a number of possible earthquakes should be considered, and a probabilistic description of the performance of the URM building (or a class of such buildings) with hysteretic damping devices should be evaluated. In this case a simple peak displacement is of limited value, and a fragility curve is a more reasonable representation for probabilistic description of building performance.

The Monte Carlo Simulation technique has been widely used in calculating the probability of exceeding a specific damage state. The Monte Carlo technique has the advantage of being able to accommodate almost any distribution, but it requires a relatively large number of simulations in order to obtain a sufficiently reliable estimate for probability of damage. It is usually impractical to simulate thousands of nonlinear building time-history analyses. An alternative approach for carrying out the structural simulation is use of a “meta-model” to represent the seismic structural performance but at a drastically reduced computational cost.

Meta-models based on response surface methodology (RSM) statistically approximate desired responses in the form of polynomial functions of random variables. The coefficients of each term in the polynomial can be obtained by first conducting detailed structural analyses on a carefully chosen sample of representative structural configurations and then using regression analysis to fit a polynomial function to the results. Monte Carlo simulations can then be performed using this response surface equation (meta-model) rather than using the time-consuming complex numerical analyses on which the response surfaces are based.

If the response surfaces are carefully constructed, the approach may also be useful for a broader class of problems, for example involving consideration of randomness in structural geometry for regional simulation. In other words, the resulting fragility curves will represent a collection of buildings with similar structural attributes in the region. In this case, a traditional design of experiments approach can be employed to define the selection of independent variables over which the structural response surface is defined. Such variables might include floor area, plan aspect ratio, height aspect ratio, stiffness and mass vertical distributions, and number of stories.

4. Completion of CBE process

In the studies described above, a single intervention was selected and assessed with regard to a single characteristic for a fairly uniform structural system (low-rise firehouses), to illustrate the fundamental approach in CBE. However a much broader expanded application of CBE is envisioned in future applications. Through analysis and demonstration of the performance of the target system under different rehabilitation schemes, CBE guides the decision maker iteratively to the set of strategies for which the consequences are acceptable, and identifies the intervention strategy that maximizes the decision maker's values. In cases where multiple decision makers are involved and have conflicting values, CBE can provide a transparent process for assessing the implications of intervention decisions.

5. Conclusions

Passive energy dissipation devices were chosen as the most appropriate intervention method for a reference URM firehouse to illustrate the overall CBE process, and resulted in reduced peak roof displacements of as much as 48%. Also, the added damping devices resulted in improved building performance, in that both building response and energy dissipation demand in the main structure were reduced.

Consequence-based engineering treats the minimization of losses as a multidisciplinary engineering activity, and counts on the active involvement of key decision makers. As illustrated here, CBE can integrate a wide variety of effective tools to reduce regional vulnerability, augment resilience capacity, and manage risk mitigation to reduce the likelihood of system collapse. However, the following are among issues remaining in the development of the CBE paradigm and will be addressed in future MAE Center research: (1) standard procedures need to be formulated for rapid assessment of consequences from approximate definitions of systems, and for identifying decision maker's goals and constraints in order to support judgments of risk acceptability and selection of interventions; (2) basic studies of decision making need to be performed to identify: (a) how various stakeholder groups react to anticipated consequences, (b) to what extent a stakeholder will be willing to invest in a parameter refinement or system intervention to reduce consequences, and (c) what types of system intervention are attractive to stakeholders for reducing consequences; (3) tools need to be improved for estimating seismic hazards in regions where earthquake records are sparse or non-existent; and (4) since a critical factor in improving earthquake decisions is the interface between the decision maker and the technical analyses within CBE, the MAE Center is developing a new generation consequence visualization module, exploiting recent advancements in information technology to synthesize information and data on the seismic hazard, regional inventory, seismic response, vulnerability and socio-economic impact.

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