EXPERIMENTALLY-GENERATED SEISMIC FRAGILITY CURVES FOR REINFORCED CONCRETE BLOCK MASONRY SHEAR WALLS

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ABSTRACT

In this paper, fragility curves, based on experimental test data, were developed as part of an ongoing research program at McMaster University focusing on quantifying the seismic performance of reinforced masonry (RM) components and systems. The program ultimately aims at developing and experimentally substantiating a comprehensive reliability-based approach to seismic design and detailing of RM construction. The current study focuses on statistically quantifying the performance of RM structural walls as the main Seismic Force Resisting System (SFRS) components in accordance with guidelines set out in recent Applied Technology Council [1] and FEMA 445 [2]. A database of previously reported experimental results [3] was used to generate experimentally-based fragility curves in an effort towards facilitating the adoption of RM as a SFRS in the next generation of performance-based seismic design codes in North America.

KEYWORDS: fragility curves, flexural failure, reinforced masonry, seismic response, shear failure, performance-based design

INTRODUCTION

In the aftermath of the 1994 Northridge Earthquake, perceived to be among the most costly earthquakes in the US history, building owners and other stakeholders recognized the need for different code philosophies to address shortcomings of the existing ones. Stakeholders showed interest in new codes that are based on quantified multilevel performance, seeing the wide scale damage occurring in code-compliant buildings after the Northridge Quake. The existing codes are based on prescriptive criteria, so that buildings designed in accordance with these codes possess certain performance capabilities, by delimiting strength and stiffness to certain minimum values and prescribing specific detailing requirements. In doing so, structures are expected to undergo inelastic deformations and sustain damages without significant loss of strength or stiffness. Nevertheless, the existing code approaches actually result in varying performance (Figure 1), absent from probability-based performance assessment as part of the design procedures. Subsequently, the Structural Engineers Association of California released a framework document (SEAOC-Vision 2000, 1995) [4] that later resulted in the publication of design guidelines such as the FEMA 273 [5], FEMA 356 [6] and ATC-40 [7], aimed at evaluating the seismic performance of existing buildings. The goals of these design guidelines shifted from those of the existing codes, essentially moving from providing minimum safety requirements for life and property (basically a single performance-based design approach) to a multi-level discretized performance-based philosophy linked to discrete hazard levels through performance objectives that accounts for all building specific characteristics and functions. Both existing and the upcoming versions of force-based seismic design codes aim to achieve these goals through deterministic means except for the determination of seismic hazard, which is done probabilistically.

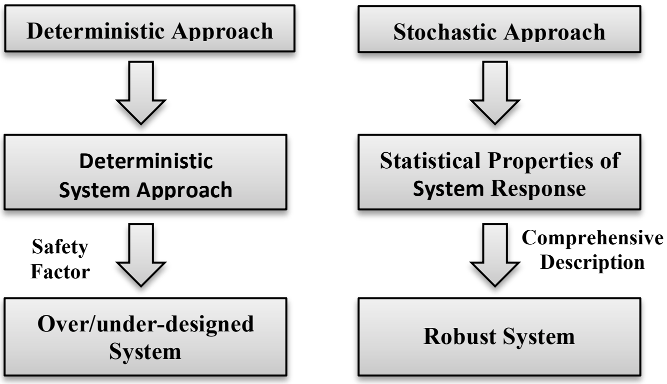

Figure 1 Design under Uncertainty [8]

PEER2- SEISMIC ASSESSMNET FRAMEWORK

Moving from a deterministic state to a comprehensive reliability-based performance assessment, espoused by FEMA 445 (2006) [2] and ATC-58 (2011) [1] as the next-generation of performance-based seismic design guidelines, current research aims to achieve this objective by providing means to quantify performance , distinguishing between different levels of damage within discrete performance levels, considering explicitly several sources of uncertainty, both aleatory and epistemic, in determining seismic demand and the structural response represented by its capacity. The new direction addresses aleatory randomness due to variations in geometrical and material properties and epistemic uncertainty due to variations in applied loading and paucity of experimental (statistical) data. The end goal of the proposed research outlined in FEMA 445 (2006) [2] is to enable users, owners, investors and other stakeholders to quantitatively assess cost versus benefits and include seismic risk alongside other types of risks, facing the building industry. This is accomplished by implementing a process aimed at estimating the probability of achieving a performance or multiple performance objectives, each of which is related to a Decision Variable (DV). These decision variables represent quantifiable decision measures that are meaningful to society and other stakeholders in their decision making process, such as replacement or repair costs, casualty rate or downtime length. This process can be presented in an abstract form by the PEER framework equation [9]:

$$\lambda(DV) = \iiint G\big((DV|DM)dG(DM|EDP)dG(EDP|IM)d\lambda(IM)\big) \tag{1}$$

where $G(x|y)$denotes the complementary cumulative distribution function of x, conditioned on y and λ(x) denotes the (MAF) mean annual frequency. Figure 2 reintroduces the terms included in the former PEER framework equation, showing each term as a part of an analysis process including Seismic Hazard Analysis, Structural and Non-structural Analysis, Damage Analysis and Loss Analysis. Each of these processes results in an output (IM: Intensity Measure, EDP: Engineering Demand Parameter, DM: Damage Measure and DV: Decision Variable). Finally, each of these variables is represented in a probabilistic form as conditional probability $p(x|y)$ to address uncertainty inherent in performance assessment. The assessment starts with probabilistic seismic hazard analysis whose output is an intensity measures that could be in the form of spectral acceleration $S_a(T_n)$ or peak ground acceleration. As such, the process aims towards establishing consensus-based input records for inelastic dynamic response simulation to reliably predict system performance in order to quantify EDP such as interstory drift ratio, floor acceleration, and inelastic deformation and associated forces.

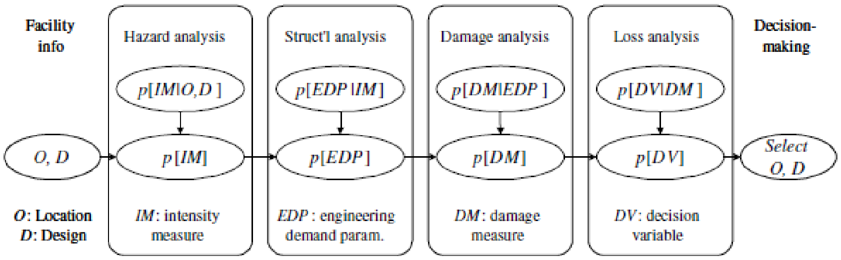

Figure 2 Underlying Probabilistic framework (Moehle and Deierlein, 2004) [10]

Once a relevant EDP has been determined, relevant probabilistic damage states to both structural and non-structural elements are to be determined [11]. Relevant damage state measures are those considered best as an input to the next analytical step, loss estimating, which requires information such as repair, enhancement or replacement cost (FEMA 306, [12], FEMA 307, [13] and FEMA 308, [14]. The output of this step is expressed in the form of fragility functions $G(DM|EDP)$, which is *the probability that a structural, non-structural component or system will experience damage at or in excess of a specific level, given that the component or the system experiences a specific demand*, the output of the previous analytical procedure. Fragility functions measure performance capability of a specific component or a system expressed in a cumulative probability distribution, driven by different methods (e.g. experimental, expert-opinion-based or analytical).

The availability of experimental data is very limited for structural components/systems and almost non-existent for their non-structural counterparts. Experimental fragility functions based on laboratory testing, as the ones developed later in this paper can be developed by different methods as listed in Table 1 and are considered more reliable [1], compared to fragility curves produced analytically. There is a gap in research that relates calculated EDP, based on inelastic simulations, and measured EDP during laboratory experiments. Such a gap limits the use of analytically-generated fragility curves, rendering experimental fragility curves the most viable (yet also the most expensive) method to developing fragility functions. However, because laboratory testing is costly and requires time, analytical methods could alternatively be used to calculate fragility functions as described by ATC-58 [1].

Table 1: Various Methods to Create Fragility Functions [15]

Method	Data Required
A. Actual failure EDP	***All specimens failed at observed values of EDP.***
B. Bounding EDP with damage	***Some specimens failed. Maximum EDP to which each specimen was subjected is known.***
C. Capable EDP	***No specimens failed. Maximum EDP to which each specimen was subjected is known. E.g., seismic qualification tests.***
D. Derived fragility	***Fragility functions produced analytically by reliability methods***
E. Expert opinion	***No data available: expert judgment is required***
U. Updating	***Enhancing an existing fragility function with new failure data***

Fragility functions developed in this paper along with others such as those developed in [16] attempt to fill the knowledge gap in this area. Most of the prior experimental testing was conducted for purposes other than developing fragility functions, such as evaluating strength and ductility capacity. As a result, recorded information is sometimes not usable for developing fragility curves. This is particularly relevant as typically more descriptive information about cracking including crack width measurement, information required to tie different damage states, experienced by a component or system, are essential so that repair or replacement cost can be estimated [14] and damage can be quantified.

Seismic IM, EDP and DM are linked together, and expressed as the probability of experiencing damage at or in excess of a specific damage state measured by the conditional probability of $G(DM|EDP)$, resulting from a certain level of demand expressed by the conditional probability of $G(EDP|IM)$, which in turn is based on particular intensity measure stated by the probability of $\lambda(IM)$, pertinent to a specific site and a structure. As a last step in the performance assessment process, estimating losses (casualties, repair, replacement cost, down time length, etc.), represented by loss function $\lambda(DV)$, the fragility function is linked through a cost function reflecting the cost of various repairs, structural enhancement or replacement, producing a probability-based loss measure, as a decision variable that could be incorporated in a decision making process by investors, developers, or other stakeholders, in any of the following forms:

- Likely losses in the event of a single scenario
- Loss with a particular probability of exceedance
- Losses associated with a continuum of scenarios
- Probability of exceeding a given level of losses in a set period of time

SUMMARY OF INVESTIGATED EXPERIMENTAL WORK

A summary of experimental work investigated in this paper is provided in [3] that included a literature review of 67 walls dominated by flexural, shear and sliding modes of failure under cyclic loading and various levels of axial loading and different amounts of both horizontal and vertical reinforcement. The objective of these experimental programs was mainly to investigate the impact of changing design parameters (e.g. aspect ratio, level of axial load, reinforcement, etc.) of masonry shear walls on their performance under test loading. Displacements were the primary measure to evaluate walls ductility and strength degradation.

DEMAND PARAMETER SELECTION

Drift will be used in this paper in developing fragility curves as it is considered the most widely adopted demand parameter in fragility analysis literature for three reasons: 1) drift values can be easily calculated from measured experimental strain values, based on beam theory, for walls dominated by flexure and are not exposed to high level of axial loads; 2) drift, being a story-height normalized wall top displacement, correlates highly with damage; and 3) drift values are used commonly in codes and literature, thus facilitating cross evaluation. Hysteresis loops, provided in the research, record lateral displacements of the tested walls, showing associated stiffness and strength degradation throughout the test. This helps tying the EDP values to reasonable damage states that help in turn in identifying the performance.

Hysteresis loops also can help evaluating the dissipated hysteretic energy as a measure of damage [17] and [18]. Additionally hysteresis loops can be used as a functional demand parameter, $EDP(\Delta_{max}, n)$, where Δ_{max} is the maximum drift value and n is the number of loading/displacement cycles were also proposed to be used in generating fragility curves [17] and [19] . The latter methods that depend on hysteretic energy will not be used in generating fragility functions in this paper

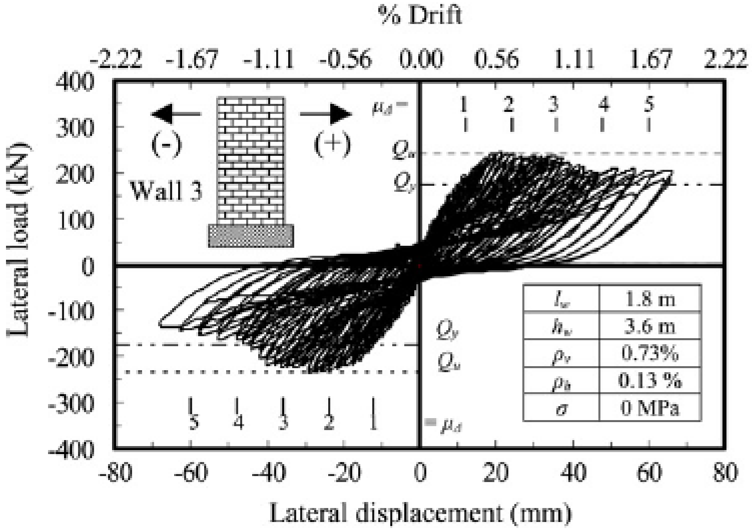

Figure 3 Hysteresis Loops (Wall 3) [20]

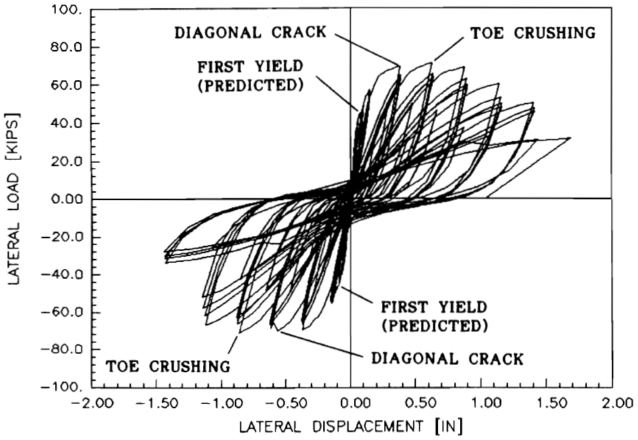

Figure 4 Hysteresis Loops (Specimen 12) [21]

DAMAGE STATES AND METHODS OF REPAIR

As explained before, identifying damage states (DS) that are relevant to estimating losses or decision variables is essential to a proper reliability-based performance assessment. Also as mentioned previously, DS are linked to estimating losses through a cost function that is based on establishing methods of repair (MoR) corresponding to each of the DS. Moreover experimental testing did not address consistently these requirements as testing was done for different objectives than creating fragility functions.

Published research in the area of DS identification such as [16], [17] and [22]presented different directions in approaching this issue, using qualitative and quantitative measures in describing walls dominant behaviour under loading. Whereas six DS to classify damages based on walls dominant behaviour (flexural, shear and sliding) were used [4] based on both quantitative and qualitative measures for walls dominated by flexure and based on only qualitative measures for walls dominated by shear and sliding mechanisms. In addition, various levels of in-plane lateral resistance in classifying quantitatively different damage states for walls dominated by flexural mechanism were specified [4]. No attempt was made to link DS to the methods of repair (MoR).Other studies, [17], on concrete squat walls, used four main DS categorized primarily by crack width as a measure to linking damage states to MoR, outlined in [14], used to group DS.

Finally, only four damage states (slight, moderate, extensive and complete) categorized by wall dominating behaviour (flexure or shear) and walls aspect ratio based on interstory drift were used in another study [10] again without attempting to link DS to MoR. Table 4 links DS to MoR, essential for estimating losses or decision variables as the last analytical step in a comprehensive reliability-based performance assessment. In this paper, damage states required for developing fragility curves are based on a criteria established by [22], shown on Table 2 and Table 3.

Table 2: Qualitative Definition of Damage States in HAZUS

Damage States	**Building Type (RM1L/RM2L*)**
Slight	***Diagonal hairline cracks on wall surfaces; large cracks around door and window openings in walls with large proportion of openings; minor separation of walls from the floor and roof diaphragms.***
Moderate	***Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger diagonal cracks. Some walls may have visibly pulled away from the roof.***
Extensive	***Most shear walls with large openings have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. Partial collapse of the roof may result from failure of wall to diaphragm connections.***
Complete	***Structure has collapsed or in in imminent danger of collapse due to failure of the wall anchorages or the wall panels.***

Table 3: Drift Ratio Comparison with Hazus

Damage States	HAZUS				Flexure		Shear	
	High-Code	Moderate-Code	Low-Code	Pre-Code	AR=1.0	1.0<AR<2.6	AR=1.0	AR<1.0
Slight	0.40	0.40	0.40	0.30	<0.25	0.20-0.50	<0.25	0.20-0.30
Moderate	0.80	0.70	0.60	0.50	0.25-0.70	0.40-0.80	0.25-0.55	0.25-0.35
Extensive	2.40	1.90	1.60	1.30	0.70-1.20	1.20-1.60	0.55-0.80	0.40-1.00
Complete	7.00	5.30	4.40	3.50	1.10-1.75	1.50-2.40	0.80-1.50	1.00-1.25

FRAGILITY FUNCTIONS

Although the documented tests [3] did not show records satisfying all the damage states listed in Table 4, the test data showed records with drift ratio exceeding the "Complete" DS and for these a fragility function, labelled "Beyond-Complete" was developed. Using the parameters listed in Table 5, fragility functions are developed for masonry walls failing in flexure and in shear indicating the probability of a component and possibly a system experiencing a certain level of DS, represented by drift value as shown in Figure 5.

Table 4: Damage State/MoR Matrix

Damage State	Flexure Dominated Behaviour	Shear Dominated Behaviour	Method of Repair
Slight	*First yield vertical steel achieved*	*First yield vertical steel achieved*	*Cosmetic Repair (MR-1)*
Moderate	*Masonry compressive strain 0.0025 achieved*	*Major diagonal cracking*	*Structural Enhancement (MR-2)*
Extensive	*Toe crushing or ultimate load achieved*	*Ultimate load achieved*	*Wall Replacement (MR-3)*
Complete	*20% load degradation*	*20% load degradation*	*Reconstruction (MR-4)*

Table 5: Fragility Function Parameters for flexure and shear dominated walls

Damage State	Demand Parameter	Flexure		Shear	
		θ	β	θ	β
Slight	Drift ratio	N/A	N/A	N/A	N/A
Moderate	Drift ratio	N/A	N/A	N/A	N/A
Extensive	Drift ratio	1.2534	0.1327	0.6401	0.3032
Complete	Drift ratio	1.9529	0.1529	N/A	N/A
Beyond-Complete	Drift ratio	3.0918	0.1356	N/A	N/A

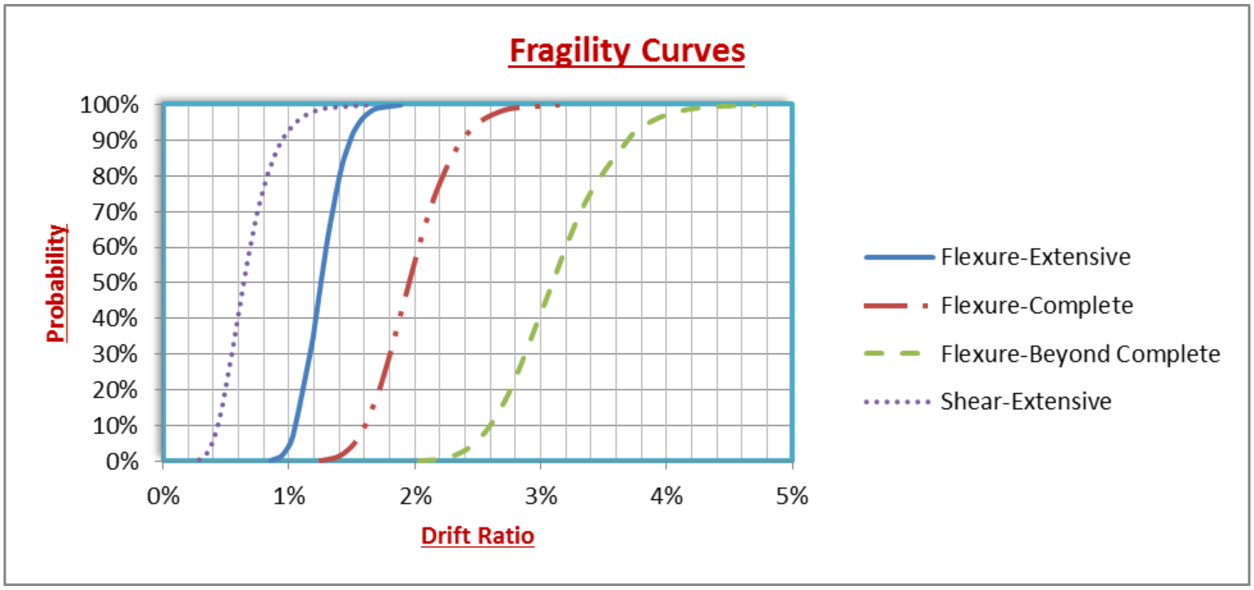

Figure 5: The Developed Fragility Curves

CONCLUSIONS AND RECOMMENDATIONS

In this paper, fragility curves were developed based on experimental data, as part of the research aimed towards implementing PEER2 framework, a comprehensive probability-based performance assessment of buildings. Although experimental fragility curves, as mentioned before, are reliable, they are expensive and time demanding. Additionally experimental fragility curves are inherently limited in geometry, structural configuration and number. On the other hand, analytical fragility curves don not suffer from these limitations and can be developed for a specific structure or an archetype, more suitable for inclusion in future building codes. For this reason, analytical fragility curves are considered more fitting to the PEER2 framework. Future research, in accordance with the guidelines currently being developed [23] is required to enhance existing simulation analytical techniques so the gap between values of engineering demand parameters, analytically produced and those based on actual measured experimental data is small. This will increase nonlinear analysis reliability, an important step towards having usable and reliable fragility curves

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