A PROCEDURE FOR ESTABLISHING FRAGILITY FUNCTIONS FOR SEISMIC LOSS ESTIMATE OF EXISTING BUILDINGS BASED ON NONLINEAR PUSHOVER ANALYSIS

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ABSTRACT :

The HAZUS methodology has been widely used for estimating the potential losses of an existing building stock caused by earthquake ground shaking for the purpose of quantifying seismic risk in a region or an urban area. Often nonlinear pushover analysis of typical buildings is required for establishing building capacity and fragility curves. This paper presents a procedure for establishing the required fragility curves for various damage states, in particular for the more severe damage states, based on nonlinear pushover analysis results. A solution is proposed for overcoming the difficulty encountered when determining the median spectral displacements for the more severe damage states. An example is given to illustrate the entire process. The proposed procedure has been successfully applied by the authors in recent seismic loss estimate studies of modern cities with densely populated buildings in regions of moderate seismicity.

KEYWORDS: Seismic Loss Estimate, Fragility Functions, Existing Building Stock

1. INTRODUCTION

Economic development and urbanisation in many countries have resulted in many modern cities where a large population and a large number of buildings concentrate in relatively small urban areas. Many people live and work in multi-storey or high-rise buildings. In regions of low and moderate seismicity often the design codes do not require any design and detailing measures for seismic resistance. However, large and destructive earthquakes could occur in regions which have been traditionally considered moderate in seismicity. An extreme example is the May 12, 2008 magnitude 8 Wenchuan earthquake which struck Sichuan Province of China. The region shaken by this devastating earthquake has traditionally been considered as a moderate seismic region. The combination of the densely populated urban environment, the economic significance of the region and the potential vulnerability of the large building stock to earthquakes warrant further investigation of the seismic risk to these buildings. The HAZUS methodology (Federal Emergency Management Agency 2003) has been widely employed to quantify the potential monetary losses to the building stock, as well as the potential number of fatalities and injuries to people living and working in the buildings. These loss estimates provide very valuable information to government emergency management agencies for earthquake disaster preparedness plans and for seismic rehabilitation strategy of existing building stocks.

An important step in the HAZUS methodology for building earthquake loss estimate is to establish, for each type of building, the fragility curves for various damage states – Slight, Moderate, Extensive, and Complete. Often nonlinear pushover analysis of a representative building is carried out to establish a capacity curve and a set of building fragility curves for each type of building. This paper presents a proposed procedure for establishing building fragility curves for the more severe damage states, based on nonlinear pushover analysis. A solution is proposed for overcoming the difficulty encountered when determining the median spectral displacements for the more severe damage states. An example is given to illustrate the entire process.

2. BRIEF INTRODUCTION OF THE HAZUS EARTHQUAKE LOSS ESTIMATE METHODOLOGY FOR BUILDINGS

The HAZUS earthquake loss estimate methodology for buildings is schematically illustrated in Figure 1. It comprises a number of modules as briefly introduced and discussed in the following sections.

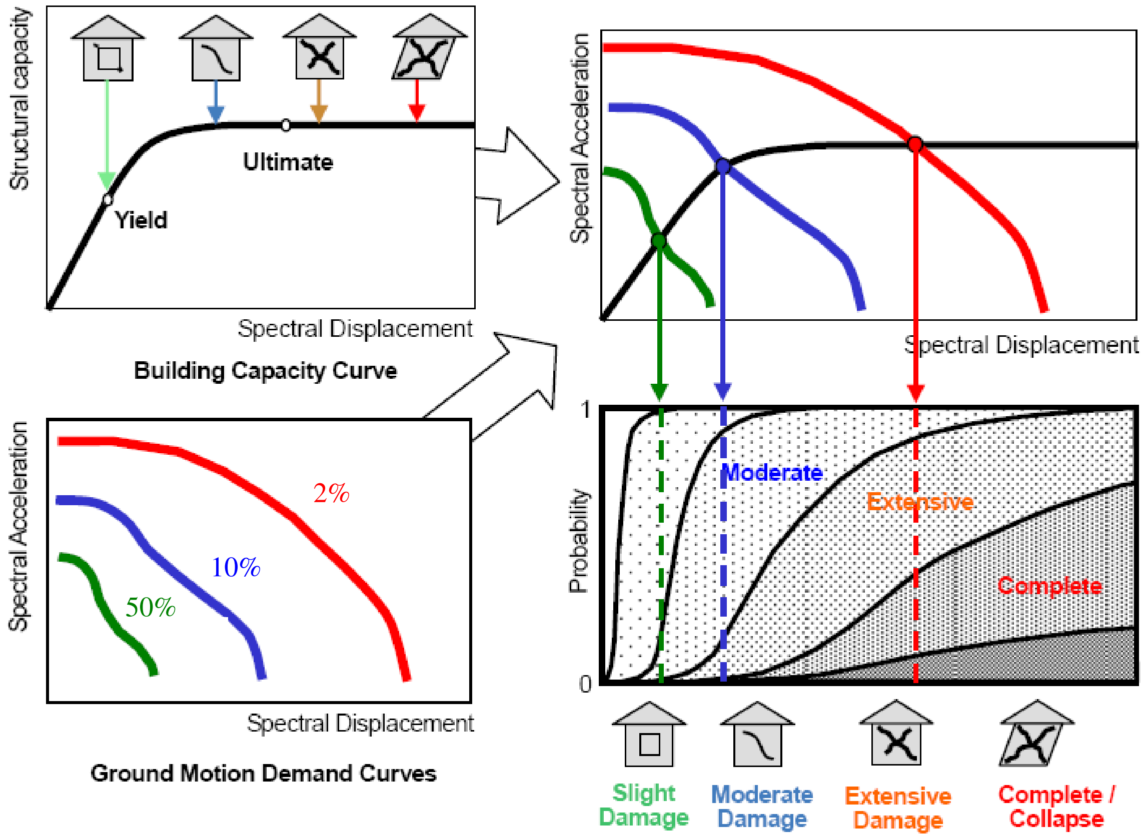


Figure 1 HAZUS earthquake loss estimate methodology for buildings

2.1. Seismic Hazard and Site Response Effects

Seismic hazard and site response effects represent the potential geo-seismic hazard illustrated by the bottom left module of Figure 1. The seismic hazard in a city or a region is often quantified in terms of uniform hazard response spectra having a 50%, 10% and 2% probability of being exceeded in 50 years for rock outcrop sites by the procedure of probabilistic seismic hazard assessment. Local site soil response effects can be established by reviewing existing geotechnical borehole data and classifying sites using the procedure described in the 2006 International Building Code (International Code Council 2006). The stiffness of the upper 30m of soil or rock is considered and classified into one of the following five site classes: A for hard rock sites, B for rock sites, C for very dense soil and soft rock sites, D for stiff soil sites, and E for soft soil sites.

The area of a city or a region may be divided into many small squares by grid lines. For instance, the spacing of the grid lines may be 100 m or greater. Each grid square is assigned a soil class, depending on the available borehole data and understanding of the geology. A representative selection of each soil class should be subjected to site soil response analysis. The ground surface response spectra corresponding to the 50%, 10% and 2% probability of being exceeded in 50 years are then established.

2.2. Response of Buildings to Seismic Ground Motion

2.2.1 Building stock inventory and population data

An inventory of buildings in the city or the regions needs to be compiled, ideally in a Geographical Information System (GIS) database. The inventory needs to record the building footprint, total floor area, the number of storeys, the building usage and the number of occupants in day and night time. The building monetary value also needs to be estimated in terms reconstruction cost. Within the database, buildings are classified into many types according to the number storeys, the construction material and the structural system. Within each type, buildings are further classified as pre-code, low-code, moderate-code and high-code, according to the level of seismic design. Generally in Asia the modern building stock is dominated by reinforced concrete buildings with some unreinforced masonry buildings in the older low rise buildings. Building heights may be divided into 5 ranges as follows:

- 1 to 2 stories and 3 stories, generally referred to as Low-rise (L) buildings
- 4 to 7 stories, referred to as Mid-rise (M) buildings
- 8 to 15 stories, referred to Intermediate high-rise (I) buildings
- 16 to 30 stories, referred to as High-rise (H) buildings
- 31 to 60 stories, referred to as Very high-rise (V) buildings

A breakdown of building structural systems may be as follows:

- Unreinforced Masonry Bearing Walls (URM)
- Reinforced Concrete Moment Resisting Frames (CF)
- Concrete Frame Buildings with Infill Walls (CFIW)
- Concrete Shear Walls (CSW)

2.2.2 Building damage states

The degree of building damage is continuous in nature, namely there are unlimited number of damage states. For simplicity, the HAZUS methodology classifies the degree of building damage into four discrete damage states: Slight, Moderate, Extensive, and Complete, as schematically illustrated in the bottom right diagram of Figure 1. Each damage state represents a range of damage to the building, with the range starting from a threshold. For example, the Slight Damage state extends from the threshold of Slight Damage up to the threshold of Moderate Damage.

Under earthquake shaking, building damage state is primarily a function of distortion or storey drift. In the inelastic range of building response, more severe damage would result from increased storey drift although lateral force would remain almost constant or even decrease. Hence, successful prediction of earthquake damage to buildings requires reasonably accurate estimation of building drift response in the inelastic range. Building capacity curves provide a simple and reasonably accurate means of predicting inelastic building displacement response for damage estimation purposes, as further discussed below.

2.2.3 Building capacity curves

A capacity curve (also known as capacity spectrum) quantifies a building's response (total lateral force divided by the building's weight, or spectral acceleration) as a function of ground motion intensity (spectral displacement or interstorey drift), as illustrated by the top left module in Figure 1.

For buildings of common types of structural systems and construction and up to typically 13 storeys in height, HAZUS has recommended default values of control points to establish the capacity curves. The HAZUS default building capacity curves depend on the degree of seismic design: pre-code, low-code, moderate-code and high-code. A building capacity curve can be divided into several segments, with each segment corresponding to one damage state, as illustrated in Figure 2.

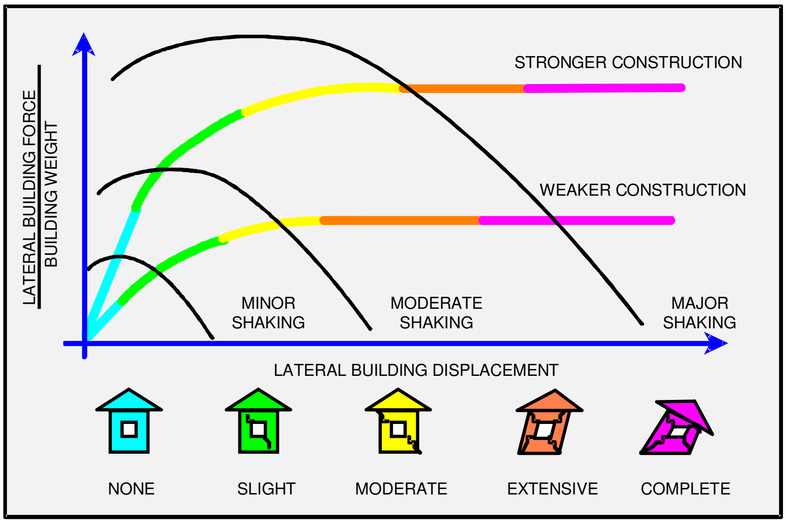


Figure 2 Determination of building response points (performance points) and correspondence between damage states and segments in building capacity curve

2.2.4 Building response

The peak building response, ie, the building damage state can be determined by the location of the so-called "performance-point" on the capacity curve. The performance point is the point at which the seismic demand curve, represented by the response spectrum curve in the spectral displacement – spectral acceleration space, intersects the capacity curve, as illustrated in Figure 2 and the top right module of Figure 1.

2.2.5 Building damage fragility curves

The probability of reaching or exceeding a given damage state is mathematically modelled by the so-called fragility curves as illustrated by the lower right module of Figure 1. A fragility curve is a cumulative lognormal probability distribution function and is determined by the median value of the spectral displacement for the *ith* damage state, $\overline{S}_{dsi}$, and a lognormal standard deviation, β. At the median spectral displacement value $\overline{S}_{dsi}$, 50% of the type of building would reach or exceed the damage state. The lower right module of Figure 1 illustrates a set of fragility curves for the various damage states.

A lognormal standard deviation is used to describe the total variability for structural damage state. In HAZUS it is often taken to include the variability of the ground motion as well as that of the building stock and also allows for variability of the capacity curve. A value of 0.5 for the natural log is a reasonable value if the seismic hazard is represented by uniform hazard response spectra that already contain specific allowance for variability of the input ground motion.

To illustrate how the capacity curve, the fragility curve and the demand curve interact with each other, the upper right part of Figure 1 shows a capacity curve and a set of three demand spectra. For each performance point a line is drawn down to the fragility curves in the lower right diagram. The percentage of the type of building that will experience Slight Damage, Moderate Damage, Extensive Damage and Complete Damage can be predicted from the corresponding intersection points between the vertical lines and the fragility curves.

2.2.6 Building loss functions

Building loss functions transform estimate of building damage to estimates of direct economical loss (percentage replacement cost), indirect economical loss (down time/business discontinuity), and casualty rates.

Figure 3 illustrates the three building loss functions for estimating the three types of loss.

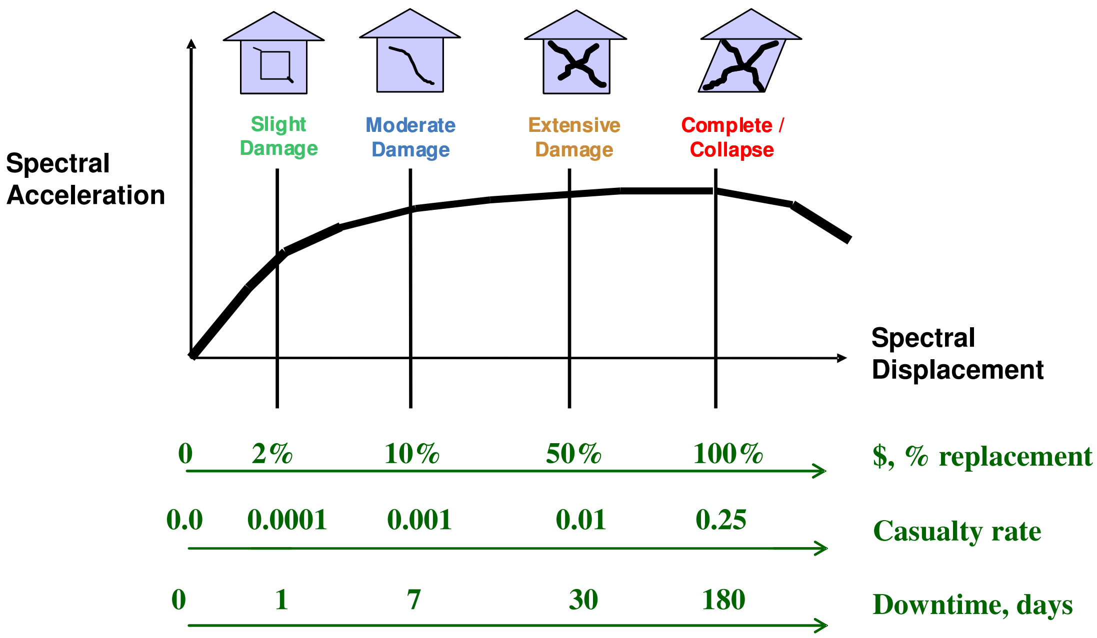


Figure 3 Building loss functions

3. DERIVING FRAGILITY CURVES FROM NONLINEAR STATIC PUSHOVER ANALYSIS

3.1. The Need

The HAZUS recommended building capacity curves and fragility curves are applicable to low-rise, medium-rise and intermediate high-rise (termed high-rise in HAZUS) buildings in the USA only. For other regions these curves need to be re-assessed for the existing building stock and also extended to high-rise and very high-rise buildings. The capacity curves and fragility curves must be established by carrying out structural analysis. While linear dynamic analysis may be suitable for some buildings, nonlinear methods are necessary if the response is significantly nonlinear. If higher mode response is significant, nonlinear response history analysis is required. However, a nonlinear static pushover analysis is preferred if appropriate.

3.2. The Analysis Method

The methodology and procedure for carrying out nonlinear static pushover analysis are well-documented in ATC 40 (Applied Technology Council 1996) and FEMA 356 (Federal Emergency Management Agency 2000). For the purpose of earthquake loss estimate, the best estimate structural component stiffness and strength capacity values are adopted to build nonlinear seismic analysis models. Such a model has the mean and the median stiffness and strength properties of the type of buildings represented by the building selected for analysis. If under a specified level of ground motion, a building's seismic response is linear or nearly linear, then its behaviour depends primarily on its stiffness and strength properties. In this case, the behaviour of the idealised nonlinear analysis model can adequately simulate the median response of the type of buildings it represents. Hence, it is relatively easy to establish the median intertorey drift ratios (or spectral displacements) for the yielding, the slight and the moderate damage states.

3.3. The Problem Encountered

However, difficulties will be encountered if the structure is shaken well into the inelastic range. In this case, the behaviour of the building depends not only on the stiffness and strength properties, but also critically on the structural components' inelastic deformation (ductility) capacities, namely their ability to develop plastic deformation while maintaining their lateral-load resisting capacity. Presently, the structural components' inelastic deformation capacity for use in nonlinear pushover analysis is commonly obtained from data recommended in ATC 40 and FEMA 356.

Because ATC 40 and FEMA 356 are rehabilitation design guideline documents, the inelastic deformation capacities recommended in these two documents are inherently conservative. Difficulties arise from this point for determining the median spectral displacements for the more severe damage states, the extensive and the complete damage states, because the ATC 40 and FEMA 356 recommended nonlinear modelling parameters and inelastic deformation capacities are not the median values.

Hence, beyond the moderate damage state, the pushover analysis results cannot be used directly for determining the median spectral displacements for the extensive and the complete damage states. The latter segments of a building's capacity curve obtained from pushover analysis underestimate the structure's inelastic deformation capacity. While this conservatism is desirable for the purpose of design of new buildings as well as assessment and rehabilitation of existing buildings, it is nevertheless unsuitable for loss estimate. Damage functions should predict losses without bias. Hence, from the point of view of building seismic loss estimate, conservatism in seismic design codes and guideline documents must be removed.

The above argument can be better understood by examining the complete damage state (also termed near collapse or collapse prevention damage state). The ATC 40 and the FEMA 356 recommended inelastic deformation acceptance limits for collapse prevention certainly are not the median values. It is not the intension of ATC 40 and FEMA 356 to provide median acceptance limits whereby 50% of the buildings just meeting the collapse prevention acceptance criteria would collapse.

3.4. A Proposed Solution

A solution proposed in this study to solve the above problem is to use the capacity spectrum from the pushover analysis, but recognising that the spectral displacement corresponding to the near collapse point is related to a much lower probability than the median value of 50%. HAZUS suggests that most engineers would likely consider the ATC 40/FEMA 356 collapse prevention criteria to correspond to a probability of between 1% to 10%. Therefore, this paper proposes the following procedure for establishing the median spectral displacements, particularly for the extensive and the complete damage states, based on nonlinear static pushover analysis results:

- Carry out a nonlinear static pushover analysis to obtain a building's capacity curve (spectrum).
- Identify the spectral displacement on the capacity curve (spectrum) at which yielding occurs. This is the median point of yielding capacity.
- Identify the spectral displacement value at which the first component reaches the complete damage state on the generalized nonlinear component force – component deformation relationship curve. According to recommendation of HAZUS, this point is the median spectral displacement for the Slight Damage state.
- The median spectral displacement value for the Moderate Damage state may be established by multiplying the median spectral displacement for the Slight Damage state by a factor of 1.5, as recommended by HAZUS.
- Identify the spectral displacement corresponding to the near collapse point on the capacity curve.
- Relate this spectral displacement to a much lower probability value on the fragility curve, between 1% to 10%, say 5% probability for instance, rather than the median value (50%), to establish the median spectral displacement for the Complete Damage state.

- The median spectral displacement for the Extensive Damage state can be determined by locating it to be midway between the median points for the Complete Damage state and the Moderate Damage state on a log scale.

3.5. An Example

An example is given herein to illustrate the solution method proposed in this paper. The building was selected as a representative of an intermediate high-rise reinforced concrete perimeter frame – central core residential building. The structure has two orthogonal principal axes and the dynamic properties along the two principal axes are similar. Linear response spectrum analysis results indicate that the interstorey shear forces from a multi-mode analysis capturing over 90% of the total participating mass are within 130% of those from a single-mode analysis. Therefore, the nonlinear static pushover analysis method is applicable to this building according to FEMA 356.

Figure 4 shows the capacity spectrum obtained from a nonlinear static pushover analysis along one of the two principal axes. The median yielding capacity point, the median point for Slight Damage, the median point for Moderate Damage, and the Near Collapse point are identified and marked on the curve, following the procedure recommended in this paper.

Figure 5 illustrates the process for determining the fragility curve for the Complete Damage state using the near collapse point in the capacity spectrum from the pushover analysis. The median spectral displacement for the extensive damage state can be determined as the spectral displacement midway between the median spectral displacement for the Moderate Damage state and the median spectral displacement for the Complete Damage state on a log scale. Finally, the fragility curves for the four damage states are given in Figure 6.

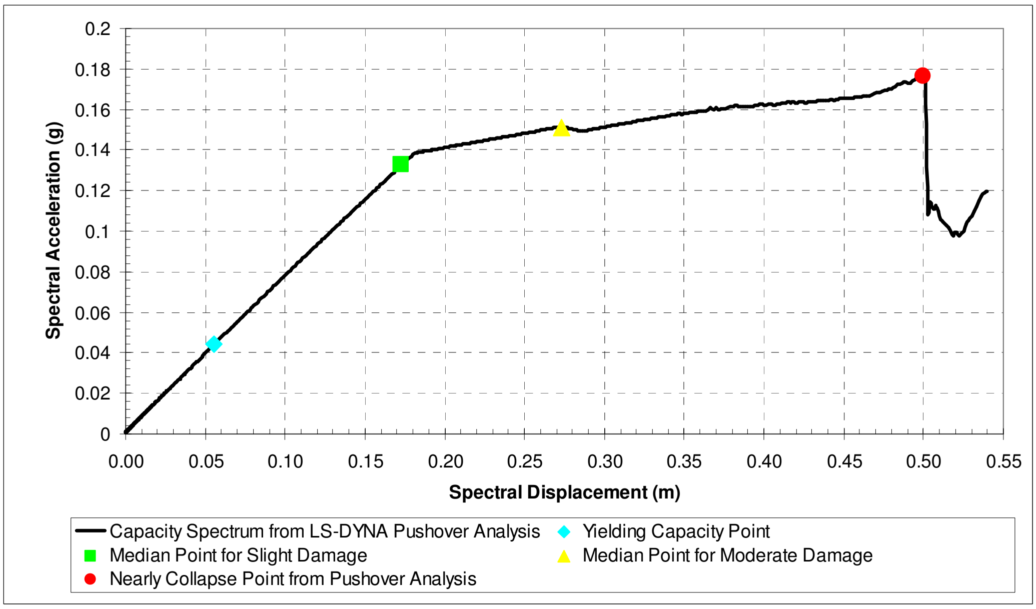
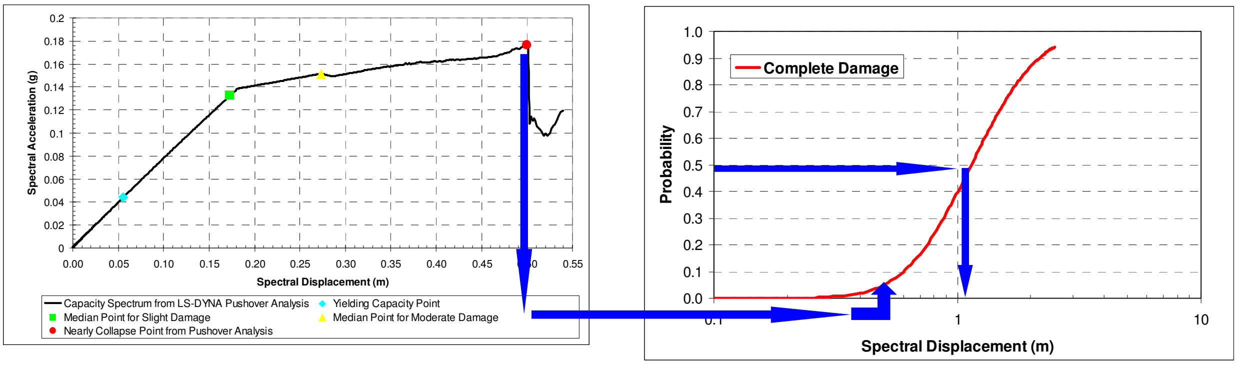


Figure 4 The capacity spectrum and locations of key points

4. CONCLUDING REMARKS

This paper has recommended a practical procedure for establishing the building fragility curves for earthquake loss estimate of existing building stocks in a city or a region based on nonlinear static pushover analysis results. The procedure has been successfully applied by the authors in recent seismic loss estimate studies of modern cities with densely populated buildings in regions of moderate seismicity.



(a) Capacity Spectrum from Pushover Analysis (b) Fragility Curve for the Complete Damage State

Figure 5 Determination of the median spectral displacement for the Complete Damage state

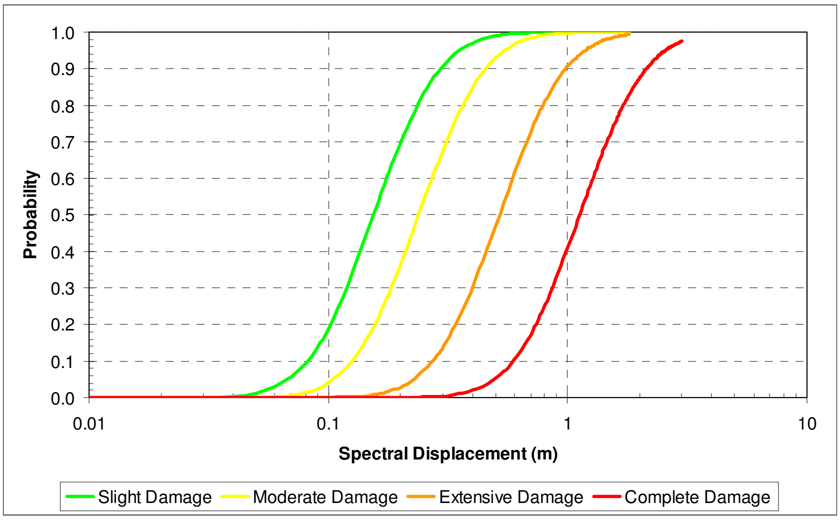


Figure 6 Derived fragility curves for the group of buildings represented by the selected building

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