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Application of the Applied Element Method to the Seismic Vulnerability Evaluation of Existing Buildings

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Abstract: As an approach to the problem of seismic vulnerability evaluation of existing buildings through the predicted vulnerability method, analytical models can be applied to define the capacity curves of typical buildings which represent different building classes. These curves are then combined with the seismic demands to produce the vulnerability curves for each of the building classes according to the damage states definition. For some buildings types, mainly the masonry structures, the development of the capacity curve is complicated and time consuming if a finite element based method is used because the model has to represent the structural geometry and relationships between different structural elements through element connectivity. Moreover, the FEM is not able to properly represent large displacements and separations for progressive collapse simulations. Therefore, the Applied Element Method which combines the advantages of FEM with that of the Discrete Element Method in terms of accurately modeling a deformable continuum of discrete materials is used here to calculate the capacity curves for those challenging building classes. This leads to a better estimation of the lateral capacity of building classes under study. In order to overcome the uncertainty in the construction material properties for existing buildings, each model is run for a vast range of material properties and the Monte Carlo method is applied to obtain the capacity curves for each building class. These curves can then be used to compare the seismic response of different building classes with a specific seismic demand or to develop scores which correlate potential structural deficiencies with structural characteristics for different classes.

1. Introduction

The predicted vulnerability method is widely used in different regions of the world to assess the seismic vulnerability of buildings when sufficient observed data is not available. As this method refers to the evaluation of the expected performance of building classes based on calculations and design specifications, analytical models can be applied to define the capacity curves which provide a representation of both the displacement and the force capacity of different building classes in terms of roof drift and base shear, respectively. For some buildings types, mainly the masonry structures, the finite element based methods used to develop the capacity curves are complicated and time consuming especially when the nonlinear behaviour and large displacements in the analytical models are of a higher concern. This paper presents the application of the Applied Element Method (AEM), an alternative to the FEM, to the seismic vulnerability evaluation of existing buildings. The method is used to develop the pushover curves for different building classes which are then combined with the seismic demands to produce the vulnerability curves for each of the building classes according to the damage states definition.

2. Seismic Vulnerability Evaluation

After a destructive earthquake in an area, buildings will be found in a range of damage states. Surveying of damages, classifying buildings into building type categories and recording damage states for each building class, can provide a relationship between the distribution of damage and the earthquake intensity level (or the ground motion). Through this type of observation, the vulnerability can be expressed in terms of damage probability matrices (DPMs) or sets of fragility curves. These matrices or functions state the probabilities that a building class will sustain different degrees of damages at given intensity levels or ground motions. To define such relationship on the basis of observed vulnerability, a considerable quantity of data is essential; where data is missing or insufficient, other methods are required to enable reasonable assessment to be made. The alternative method to be used to obtain the damage probability relationship with ground motion parameters is the predicted vulnerability which refers to the evaluation of the expected performance of building classes based on calculations and design specifications.

The capacity curves can be established through analytical models of typical buildings, representing different building classes. These curves are then combined with the seismic demands to produce the vulnerability curves for each of the building classes according to the damage states definition. Therefore, the following 3 basic elements are required for any seismic vulnerability evaluation method which applies analytical modeling.

1) A building classification that properly classifies the existing structures based on their structural characteristics and constructional materials
2) A clear and precise definition of the damage states for the buildings
3) Typical capacity and fragility curves for each building group

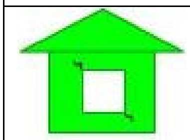
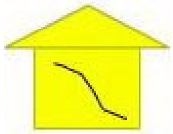
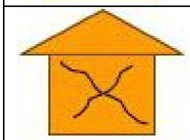
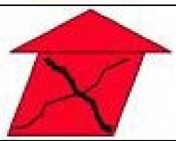
The building classification can be developed through an exhaustive study of the existing buildings in the region. A good classification should be able to comprehend, if not all but the majority of the building types in the area and consider both the structural characteristics and the construction materials in its categorization. An example of this is the building classification proposed for the historical sectors of Quebec (Table 1).

Table 1. Proposed Building Classification For Historical Sectors Of Quebec (Karbassi and Nollet 2007)

Structure Type	Description
Wood Structures	Light Wood Frame Wood Beams and Columns
Steel Frame	with Bracing with Concrete Shear Walls with Infill Masonry Walls Moment Resisting Frames
Concrete	Frame with Infill Masonry Walls Moment Resisting Frames
Masonry	with Rubble Stone with Simple Stone with Massive Stone Unreinforced Masonry with Wood Floors

The definition of the damage states can be presented for each building class, such as the European Macroseismic Scale (Grünthal et al. 1998), or it can be defined separately for structural and non-structural systems within each building class (NIBS 2003) as shown in Table 2. A clear explanation of the damage states helps to determine the control points (yield, ultimate capacity, etc.) on the capacity curves and to select the parameter of the building response that best represents the threshold of each damage state. These thresholds are then converted to spectral response values to develop the fragility curves.

Table 2. Damage State Definition for Unreinforced Masonry Bearing Walls (URM) (NIBS 2003)

Damage State		Description
	Slight	Diagonal, stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of opening; movements of lintels; cracks at the base of parapets.
	Moderate	Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.
	Extensive	In buildings with relatively large area of wall openings, most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their supports.
	Complete	Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of the walls. Approximately 15% of the total area of URM buildings With complete damage is expected to be collapsed.

To develop the typical capacity curve for each building group, a suitable analytical method which can produce an accurate model for the building classes' representations should be chosen. The Finite Element based methods have been considered as the main tools for this mean. However, the procedure requires the consideration of nonlinear behaviour of the structural elements and large displacements which can happen during an earthquake. Moreover, in some cases, the effects of the non-structural elements are significant and can not be ignored for the simplicity of the model. Therefore, the application of any FEM in these cases would be complicated and time consuming because those methods assume the material as a continuum. This means that special techniques must be adapted to consider the separation of structural members. In most cases, the fracture plane is arbitrary and unknown before analysis.

The Applied Element Method (AEM) which is based on dividing the structural members into virtual elements connected through springs can be used as an alternative. In this method, each spring entirely represents the stresses, strains, deformations, and failure of a certain portion of the structure (Meguro and Tagel-Din 2002). The main advantage of this method is that it can represent the structural behaviour from the initial loading stages up to its complete collapse.

3. Finite Element vs. Applied Element Method

The application of the Applied Element Method for the analysis of structures subjected to the possibility of cracking, elements separation, and collapse is a major breakthrough when compared to the current methods for analysis being used, most notably the Finite Element Method (Tagel-Din and Rahman 2006). In any FEM-based analysis, elements are connected at nodes and therefore it is assumed that all the elements sharing the same node have the same displacement. However, in a progressive collapse analysis where the element separation is expected, element displacements must be treated independently to accurately track the behaviour of each element when separation occurs and this is a phenomenon which the FEM is incapable of smoothly dealing with. Some researches have suggested the idea of using multiple node IDs at expected separation points but this technique results in stress singularity and inaccurate stresses at locations of nodal separation, which leads to an unrealistic stress distribution within the whole structure. Moreover, it is not always possible to pre-determine the location of cracks in the elements (e.g. for orthotropic materials like masonry) especially in a progressive collapse case.

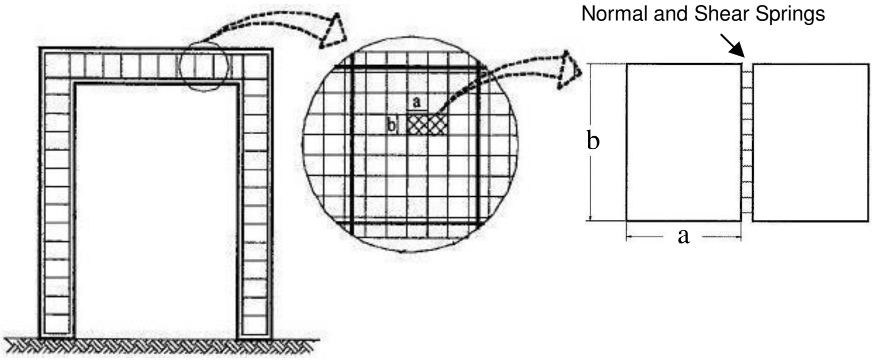


Figure 1. Structure Modeling in AEM (Meguro and Tagel-Din 2002)

Unlike the FEM, in the Applied Element Method, the elements are connected through a series of springs on their surfaces (Figure 1). These springs represent stresses, strains and connectivity between elements. Therefore, partial connectivity between the elements is allowed during the analysis and some of the springs can fail while others are effective and their failure will not cause any type of singularity in the model. Table 3 shows the possible analysis domains of AEM in comparison with FEM.

Table 3. Analysis Domains of Applied Element Method (Tagel-Din and Rahman 2006)

	Small Displacement		Large Displacement		Collision
	Elastic	Nonlinear	Geometrical and Material Changes	Element Separation	Progressive Collapse
FEM	Accurate	Reliable Results		Develop.	Not Covered
AEM	Accurate	Reliable Results			Develop.

4. Development of the Capacity Curves

4.1. Application of Applied Element Method

As a result of the FEM limitations to assess the behaviour of existing buildings in progressive collapse cases and its complexity to model some buildings types, mainly the masonry structures, an AEM-based software such as the Extreme Loading® for Structures (Applied Science International 2007) is used as an alternative. In this way, the model can provide a comprehensive analysis and visualization of structural behaviour during different loading stages from small displacement in the elastic mode to element separation and building collapse.

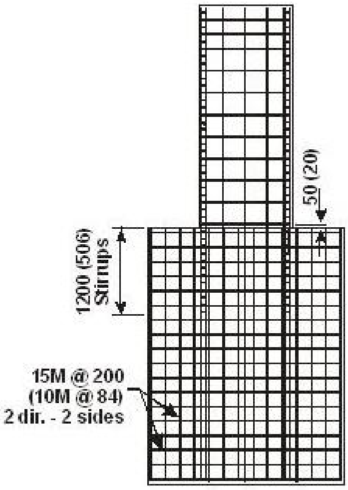


Figure 2. Plan View of the Concrete Wall Under Monotonic Loading (Ghorbani-Renani et al. 2008)

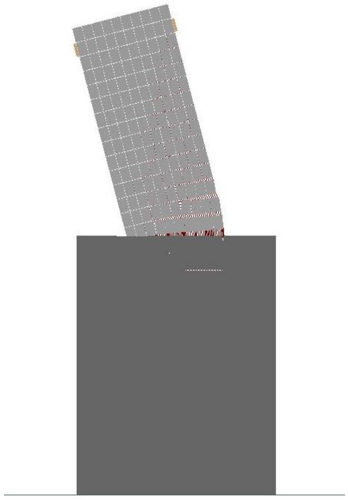


Figure 3. Pushover Analysis of the Shear Wall

In order to validate the accuracy of the tool to represent the nonlinear behaviour of masonry or concrete structures in the pushover loading, the results of various experimental tests have been compared with the analytical models outputs. As an example, the experimental result of the monotonic loading on a concrete shear wall (Figure 2) is compared with the output of the pushover analysis.

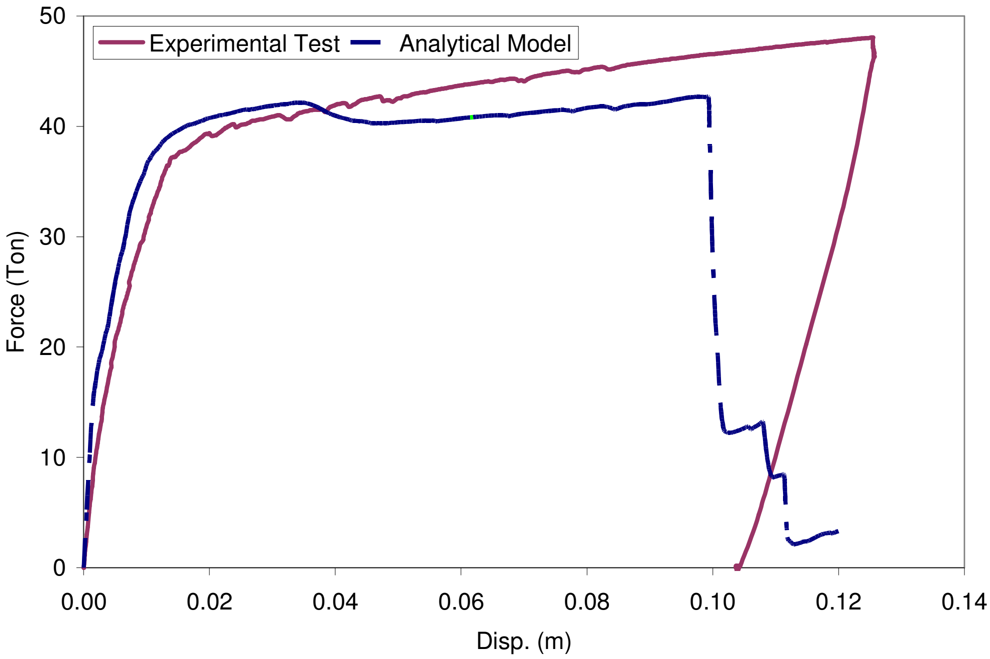


Figure 4. Load-Deformation Curve: Pushover Analysis and Experimental Test

The results from the analytical model coincide with the experimental test in the linear and nonlinear area (Figure 4). The divergence of the two lines in the collapse mode can be explained as a result of the reinforcement confinement in the analytical model which causes it to fail sooner than the experimental test.

The Applied Element Method is used to develop the typical capacity curves of the building classes in Table 1; as an example, the capacity curve of a 6-story industrial masonry building (built in 1905 in old Montreal) with wood floors (Figure 5) is developed through the pushover analysis. Because of the high number of the openings in the outside walls, it is expected that the post-elastic behaviour of the structure would be different from a typical masonry building which usually collapses after the walls reach the yield point (without any nonlinear behaviour). The load pattern used here for the pushover analysis is in proportion to building first mode of vibration. Figure 6 shows the force-displacement curve of the top story in the longer direction (East-West).

Figure 5. Industrial Building South View: 6-Story Masonry Structure with Wood Floors

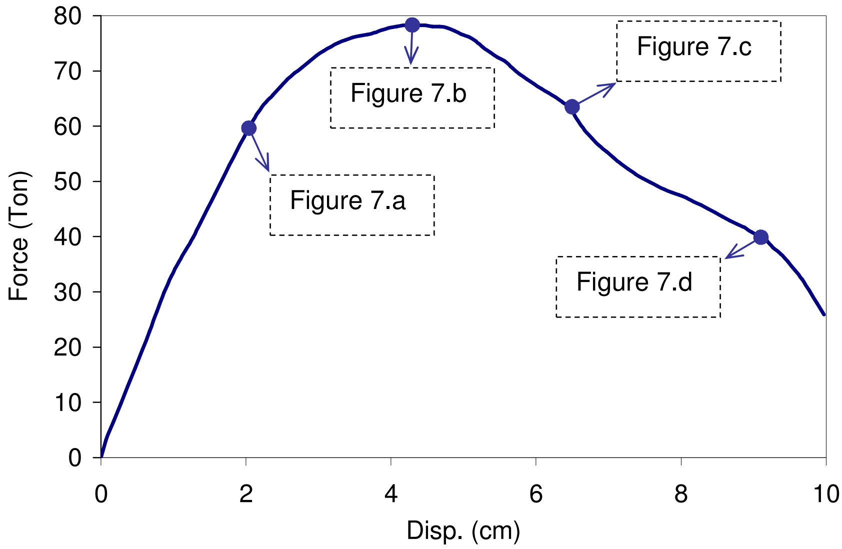


Figure 6. Force-Displacement Curve of the Roof in the Longer Direction (East-West)

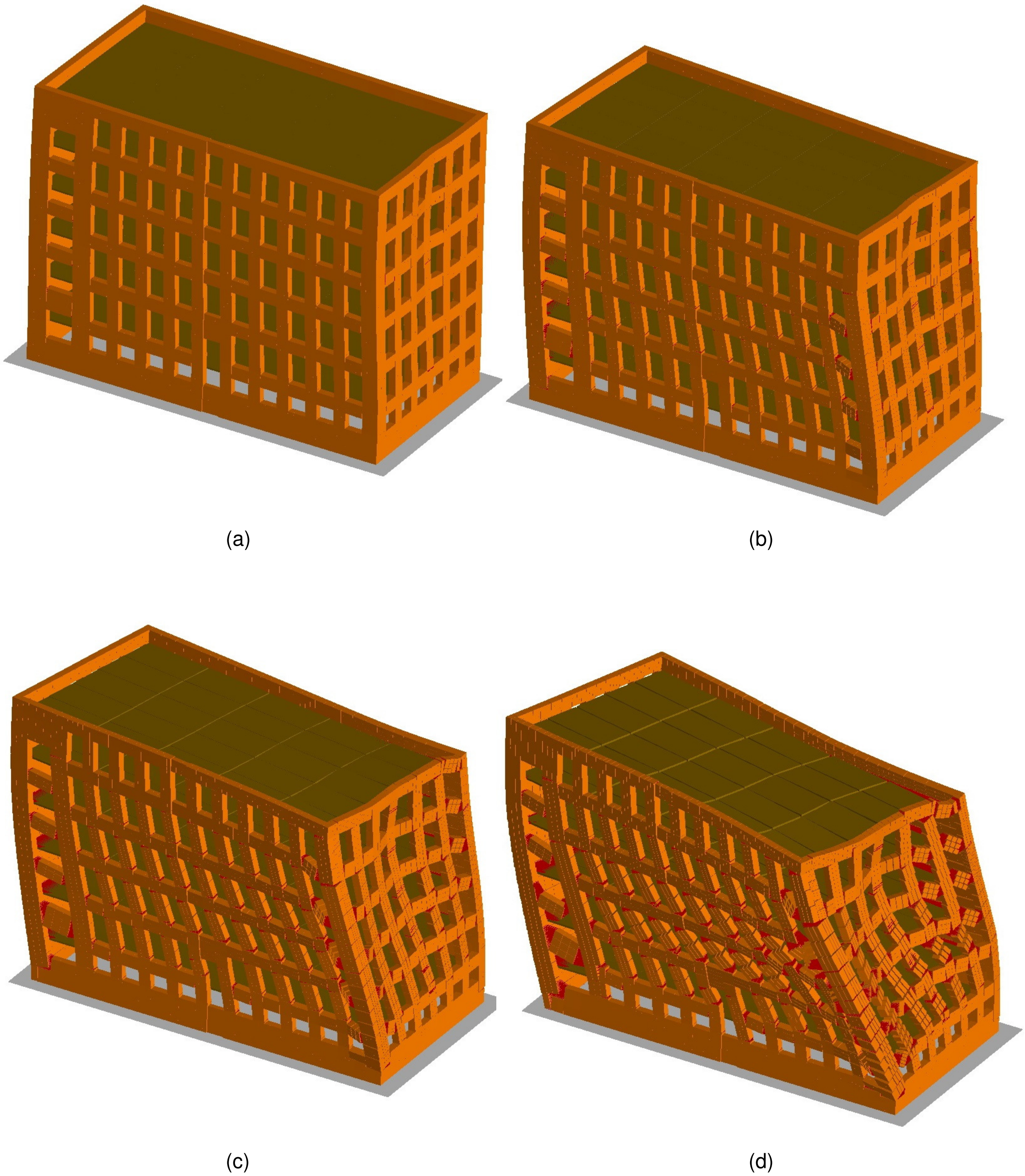


Figure 7. Structural Damages in the Masonry Building at Different Steps of the Pushover Analysis

The damage states "slight", "moderate", "extensive", and "complete" are shown on the capacity curve of the building according to the definition given in Table 2 and based on the observation of the structural damages (Figure 7) in the building. Figure 7.a shows the point on the capacity curve after which the building enters the nonlinear phase. At this step there are some hairline cracks on masonry wall surfaces and large cracks have developed around the windows. At the moderate damage state, Figure 7.b, the building starts loosing strength because of the significant cracks everywhere. Figure 7.c shows the stage where there are large areas of wall openings in the building and most walls have suffered extensive cracking. Because of the extensive damages in the building shown in Figure 7.d, it is expected that the structure is in an imminent danger of collapse.

4.2. Monte Carlo Simulation

The accuracy of the analytical models depends on the precision of the basic assumptions considered in their developments. Issues relating to the accuracy of mathematical models mainly include the uncertainty and variation in the actual material properties and dimensions of the as-built structure and differences between the actual component strengths and values used in the analytical model. To overcome the uncertainty in the construction material properties for existing buildings, the Monte Carlo simulation is applied to obtain the capacity curves for each building class. For each uncertain variable (material yield strength, ultimate strength, stiffness, etc.), possible values are defined with a probability distribution based on the conditions surrounding that variable and the model is run for that range of material properties. The results are the most probable capacity curves for each building group.

5. Fragility Curves

The control points shown on Figure 6 are used to develop the fragility curves for each building group in Table 1 by relating the building deformations to the structural damage-states representation. The procedure to develop those curves from analytical methods consists of the following steps.

1) Selection of specific values of building response (e.g., average inter-story drift, roof displacement) that best represent the threshold of each discrete damage state.
2) Conversion of the damage-state threshold values to spectral response coordinates (i.e., same coordinates as those of the capacity curve)

Using the detail descriptions of each damage state for each of the building classes, the building deformations can be related to the representations of structural damage-states. This can be the building response that best represents the threshold of each damage state. The threshold of each damage state is then detected on the pushover curve (Figure 6). The next step is to convert the damage thresholds to spectral response values. The "median" values of the building response representations can then be converted to median spectral displacement values (for each damage state) which are used as the point with 50% probability on the fragility curve.

The slope of the fragility curve is controlled by the lognormal standard deviation value (Beta). The smaller the value of Beta, the less variable the damage state would be, leading to a steep curve. Three primary sources seem to contribute to the total variability of any given damage state, namely, the variability associated with the capacity curve, the variability associated with the demand spectrum, and the variability associated with the discrete threshold of each damage state (NIBS 2003).

The fragility curve of the industrial masonry building (Figure 5) is developed in Figure 8 using the control points shown on its capacity curve (Figure 6) as the threshold of the different damage states. It should be noted that in Figure 8, the x-axis is the roof displacement; therefore, each curve shows the probability of the building exceeding a specific damage state given the roof displacement.

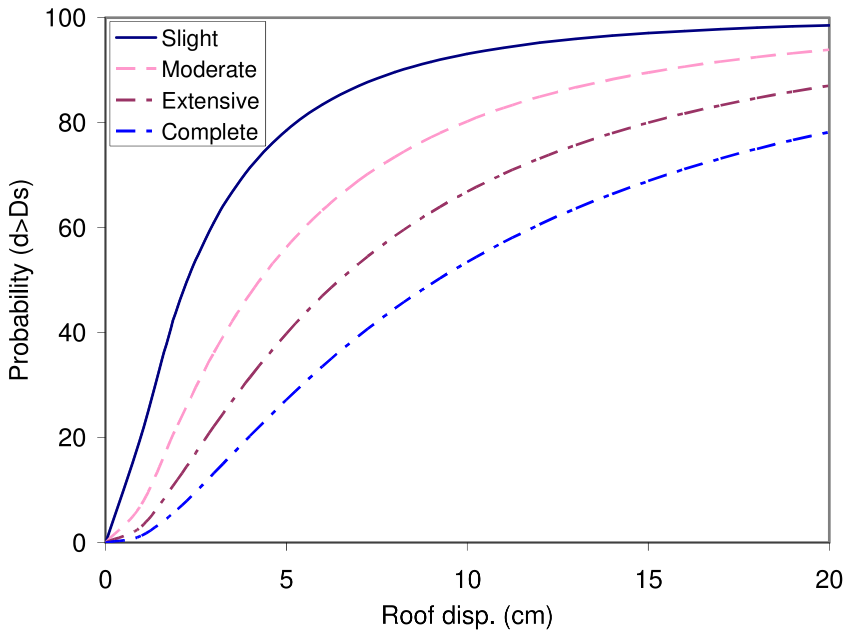


Figure 8. Fragility Curves of the Longer Direction of the Industrial Masonry Building

6. Conclusion

As an approach to the problem of seismic vulnerability evaluation of existing buildings using the predicted vulnerability method, an alternative to the Finite Element Method was presented in this paper. Because of the FEM limitations in modeling large displacements in the elements and their separation, the FEM-based methods are not the most suitable tools in a progressive collapse case. Moreover, it is not always possible to pre-determine the location of cracks (FEM solution to model large displacements) in the elements (e.g. for orthotropic materials like masonry). Therefore, the Applied Element Method (AEM) which is based on dividing the structural members into virtual elements connected through springs can be used for the seismic vulnerability evaluation of buildings. In this method, each spring entirely represents the stresses, strains, deformations, and failure of a certain portion of the structure.

The application of the method to the nonlinear analysis of a typical industrial URM building of 1900's was presented to illustrate how the method can be used to develop the capacity curves of different building classes. Through the definition of different damage states for each building class, a numerical value can be assigned to each damage state on the capacity curve as the control points which are used to develop the fragility curves. These curves can then be used to compare the seismic response of different building classes with a specific seismic demand, which correlate potential structural deficiencies with structural characteristics for different classes.

7. Acknowledgments

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