Advanced Component Method (ACM™) - An Objective Methodology for the Assessment of Building Vulnerability

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Abstract: This paper describes a new objective methodology for modeling building vulnerability. The methodology is called Advanced Component Method (ACM™). ACM is a major attempt to replace the conventional loss estimation procedure, which are based on subjective measures and the opinions of experts, with one that objectively measures both earthquake intensity and the response of buildings. First, response of typical buildings (for example, mid-rise steel moment frame or low-rise concrete shear wall) is obtained analytically by nonlinear seismic, or pushover, analyses. Spectral displacement is used as a measure of earthquake intensity. Damage functions for each building component, both structural and non-structural, are developed as a function of component deformation. Examples of components include columns, beams, floors, partitions, glazing, etc. A cost model is developed that maps the physical damage to monetary damage for each component. Finally, building response, component damage functions, and cost model were combined probabilistically, using Monte Carlo simulation techniques, to develop the final damage functions for each building type. Uncertainty in building response resulting from variability in material properties, loads, etc. component damage functions and cost model were incorporated in the Monte Carlo simulation. The paper also presents and compares damage functions developed for several building types.

1 Introduction

Recently, earthquakes in Turkey, Taiwan, and elsewhere refocused attention on the ability of catastrophe modelers to estimate, more reliably and accurately, building damage and corresponding monetary losses in the face of future events. As becomes immediately apparent in any post-earthquake field investigation, the intensity of earthquakes, as measured by the damage that results, is not uniform but spotty, even for locations with similar soil conditions and at equal distance from the rupture. In order to better understand this phenomenon, to model it, to make more reliable estimates of building damage, a new methodology, called Advanced Component Method (ACM™), has been developed.

This paper describes the ACM. Existing vulnerability assessment methodologies are revisited first. Their advantages and shortcomings are compared. The advantages of ACM to address the potential shortcomings of existing methodologies are discussed. ACM methodology of developing building damage functions is described. The methodology has several stages including building design, pushover analysis, component damage functions, and cost model.

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Each stage is described separately. Finally, some of the damage functions obtained from ACM are presented.

2 Existing Methodologies

The science of vulnerability assessment, that is, of estimating the probability and extent of earthquake damage before an earthquake occurs, is still very young. Most attempts have been based on simple extrapolations from observed damage in the aftermath of earthquakes or, given their relative infrequency, on the opinion of experts as to what might result were an earthquake to occur. Two most notable attempts to address vulnerability assessment were ATC-13 (1985) and HAZUS (1997) studies. Following section describes both methodologies and compares their advantages as well as shortcomings.

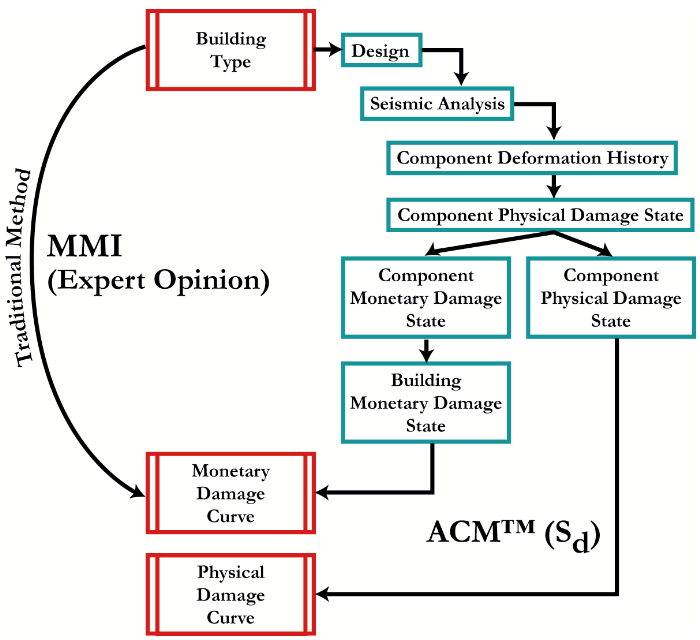

Figure 1: A flow chart of ACM compared with traditional vulnerability assessment methodologies

2.1 ATC-13

One of the first systematic attempts to quantify building vulnerability to earthquakes came from the Applied Technology Council in a report to the Seismic Safety Commission of the State of California, ATC-13 [1]. ATC-13 essentially derived damage functions by asking experts to estimate the expected percentage of damage that would result to a typical building of a specific construction type were that being subjected to a given MMI. Based on their personal knowledge and experience, the experts responded to a formal questionnaire with their best estimates of damage ratios.

Because it was the first systematic attempt to develop damage functions, ATC-13 quickly became the standard reference for earthquake vulnerability assessment. Catastrophe modelers adopted the ATC-13 damage curves virtually unaltered until the 1994 Northridge earthquake.

After that event, an attempt to modify the ATC-13 curves was made using actual claims data from Northridge.

2.2 HAZUS

A second major effort to develop a methodology for vulnerability assessment was undertaken by the National Institute of Building Sciences (NIBS), and funded by FEMA. The result, HAZUS, was released in 1997 as a risk assessment interactive software [2]. In HAZUS, spectral displacements and spectral accelerations replaced MMI as the measure of seismic intensity, The focus shifted from ground motion to the individual building's response to ground motion. This objective measure of earthquake intensity allowed for finer gradations in estimating the potential damage to a structure. However, the HAZUS study continues to rely on expert opinion and engineering judgement to estimate the state of damage that would result from a given spectral displacement and acceleration. While HAZUS represent a significant advance, the difficulties surrounding reliance on expert opinion remain.

3 ACM

Considering the shortcomings of both ATC-13 and HAZUS methodologies, ACM attempts to provide a major improvement on the existing vulnerability assessment techniques. ACM replaces the subjective measures and opinions of experts about how building damage relates to earthquake intensity with an objective and scientific methodology. ACM is also a very transparent method. Because the underlying parameters are accessible and the significance of each is well understood, ACM can be easily calibrated. Likewise, it can be easily modified to incorporate the results of new research and experimentation. It can be extended to include new building types and new regions. It can be updated as repair costs change and new repair strategies are introduced. Figure.1 describes a general flow-chart of developing ACM damage functions as compared to traditional methods, such as ATC-13, of developing damage functions.

ACM replaces earthquake intensity of MMI with spectral displacements. Spectral displacement is the maximum horizontal displacement experienced by the equivalent SDOF system of the building during an earthquake. The building damage is calculated from the spectral displacement. Existing methods estimate building damage from MMI or PGA which are not a measure of building response rather a measure of ground motion. Because each building has a different natural period, each will be subjected to a different seismic intensity (spectral displacement) and, hence, a different damage state. For example, an earthquake of magnitude 8.0 occurring at a distance of 50km and an earthquake of magnitude 5.0 at a distance of 5 km may well produce the same PGA at a certain location. Using the conventional method for assessing vulnerability, these two earthquakes will subject a building to the same intensity and will therefore result in the same level of damage. But the spectral ordinates of these two earthquakes may be quite different and, accordingly, the building's response will be quite different. The use of MMI or PGA as the measure of intensity will result in a relatively narrow distribution of damage, which will not reflect the spottiness of damage that is actually observed. Because of using spectral displacements as a measure of earthquake intensity, ACM can capture this spottiness of damage.

4 Developing ACM Damage Functions

Second breakthrough of ACM is the way it develops building damage functions. As pointed out earlier, existing methodologies rely on damage functions developed based on expert opinions. ACM uses totally objective analytical and experimental tools to develop building damage functions. Following section describes different stages of developing these damage functions.

4.1 Building Design and Modeling

The first step in developing ACM damage functions is to identify buildings typical of the modeled region and define general configuration and characteristics. Actual design plans are created for each building type. Design documents include the physical dimensions of each component, as well as their axial, bending, moment and shear capacities, yield strength and other material properties. Each building type is to be as representative of the average in the modeled region as possible.

In order to incorporate the variation from the typical building, a number of parameters of the building are assumed to be random variables. Table 1 shows a complete list of parameters selected as random variables. Table 1 also shows their means and coefficient of variables with corresponding distributions. As a result, a number of buildings were created from a single design. Then a finite element model of each building was developed.

Table 1: Random variable and their distributions

Random Variable	Mean	COV	Distribution
Roof mass at edge	0.0313	0.18	Normal
Roof mass in middle	0.053	0.18	Normal
Floor mass at edge	0.0701	0.18	Normal
Floor mass in middle	0.1378	0.18	Normal
Roof dead load at edge	0.0378	0.1	Normal
Roof dead load in middle	0.0183	0.1	Normal
Roof live load at edge	0.0042	0.6	Type I Largest
Roof live load in middle	0.003	0.6	Type I Largest
Floor dead load at edge	0.0836	0.1	Normal
Floor dead load in middle	0.0479	0.1	Normal
Floor live load at edge	0.0104	0.6	Type I Largest
Floor live load in middle	0.0075	0.6	Type I Largest
Modulus of elasticity of steel	29000	0.05	Normal
Modulus of elasticity of concrete	3605	0.05	Normal

Steel yield strength	39	0.14	Log-normal
Concrete strength	3400	0.11	Normal
Yield strength of reinforcing bars	67	0.11	Log-normal

Latin Hyper-cube sampling is chosen to represent uncertainties in structural parameters in calculating the response statistics by simulation [3]. It is a stratified sampling method, and is comparatively efficient for estimating the response statistics when no closed-form relationship between structural response and variables (material strength and loading) is available, and when the number of samples is limited. Figure 2 illustrates the procedure.

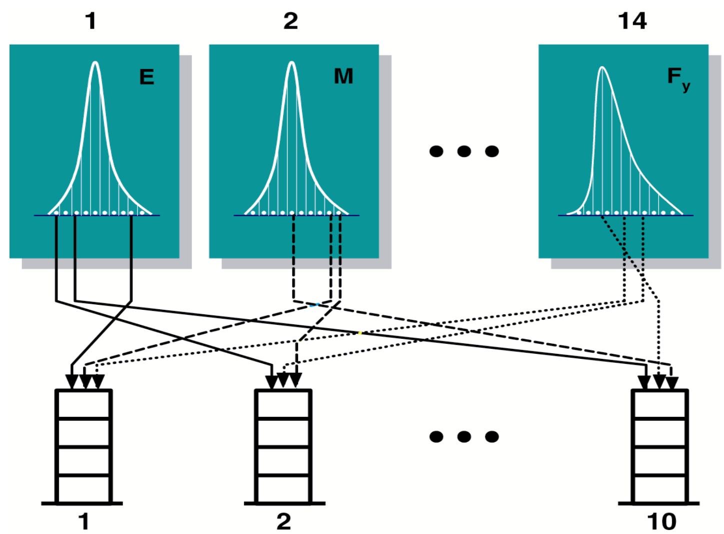

Figure 2: Combining uncertainties using Latin Hyper-cube Sampling technique

4.2 Calculating Building Deformations

Once a three-dimensional model of each building was built, a three dimensional push-over analysis was performed to calculate building deformations. Push-over analysis was performed by applying the building a lateral load along its height. SAP 2000 software [4] was used to perform the analysis. The lateral load is proportional to the first mode shape of the building. The load is applied incrementally until the building collapses. At each stage, lateral force is distributed to the beam-column connections. As connections and members fails, the force is redistributed to the elements that remain functional. Lateral forces are applied in two directions, separately, and the effects are combined to archive a three-dimensional analysis that captures the building's dominant modes of vibration and approximates the results of a time history analysis.

First product of pushover analysis is building capacity curves. Building capacity curves describe the relationship between the building displacement and the force applied. Building displacements are calculated based on an equivalent Single-Degree-of-Freedom-System

(SDOF). Figure 3 illustrates a series of capacity curves developed for the five story Steel Moment Resisting Frame (SMRF) building. Due to the inherent uncertainty in both material strength and loading process, one would also expect uncertainty in the behavior of the building response to dynamic loading. The variability in the capacity curves is a good measure of the uncertainty. It is captured here for further uncertainty convolution in vulnerability estimation.

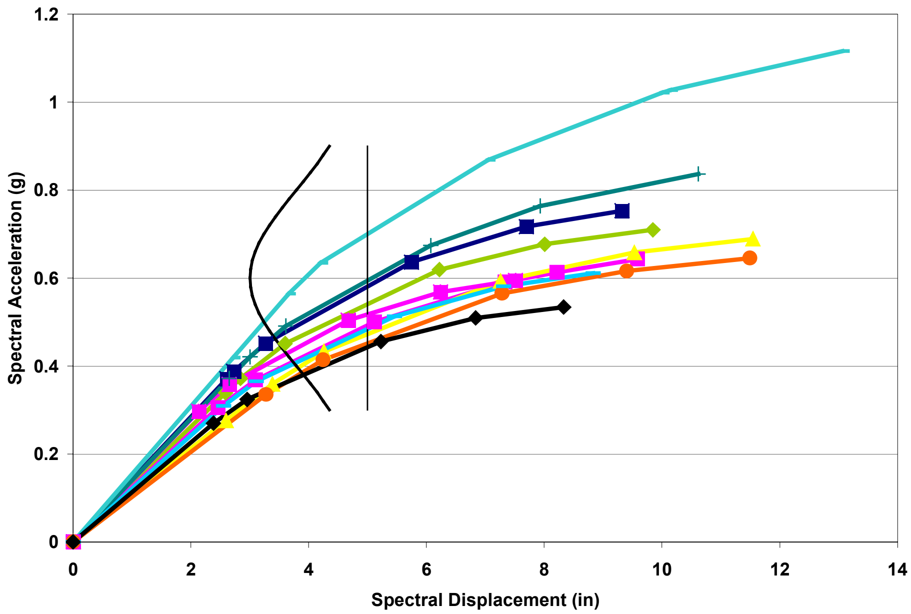

Figure 3: Set of capacity curves obtained from five story Steel Moment Resisting Frame building

The second product of pushover analysis is floor deformations. As the lateral force applied, building deforms proportionally. For each incremental displacement of the building, the amount by which components at each of the floors are deformed, which are shown in Figure 4, will determine the inter-story drift. Inter-story drift ratios are calculated and used to calculate component damage ratios as will be explained in the following section. As in the case of capacity curves, uncertainties are also captures in drift ratios.

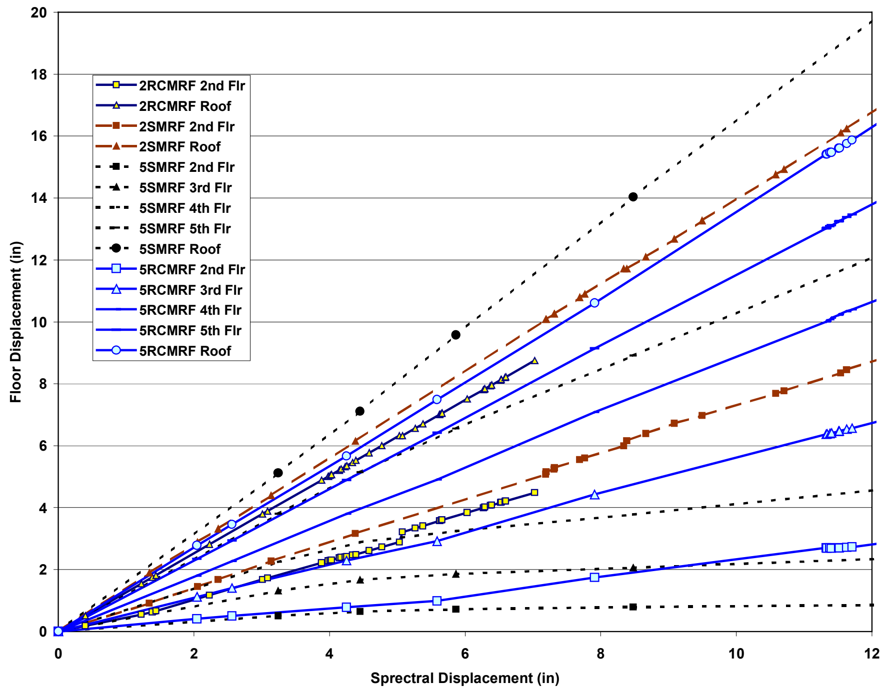

Figure 4: Story displacements from various building types calculated by push-over analysis

4.3 Calculating Component Damage

Historically, problem of estimating building vulnerability has been approached as a whole. In other words, damage to a building was calculated at once. This estimation was usually achieved by means of expert opinion because of the complexity of the problem. However, ACM approaches the problem in a totally different way in order to solve it objectively. ACM, first, breaks the building into its components of manageable portions. Those components include columns, beams, partitions, etc. Criteria for selecting each component were that one should be able to obtain an individual function describing damageability of each component. Combining the data obtained from the experimental studies conducted at various universities and research organizations in a probabilistic manner developed these individual damage functions. Figure 5 shows some of these individual component damage functions.

Damage on each component under a given earthquake intensity, described by the spectral displacements, can be calculated from the individual component damage functions. These damage rations are then summed over each floor and components to obtain building damage ratio. Hence the final number, obtained through an objective methodology, is much more reliable compared to existing methodologies.

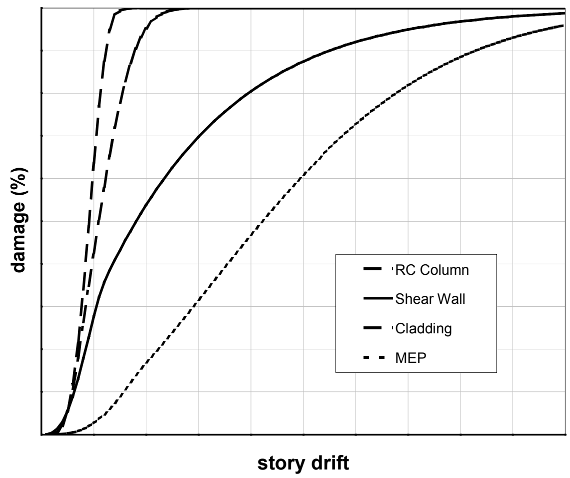

Figure 5: Selected component damage functions

4.4 Cost Model

Previous section describes the calculation of physical damage ratios. However, monetary losses, defined by the repair cost of the damage caused by the given earthquake are calculated differently. ACM estimates monetary damage at the component level and the component damages are subsequently aggregated to produce building monetary damage curves.

The first step in developing the cost model is to estimate the total cost of building that is the cost of constructing the building as a new project. Total replacement cost is then calculated by adding the cost of demolishing the old building. The total cost of the building is calculated by estimating the cost of each individual component including the ones that individual damage functions were developed in the previous section. All cost related information was obtained from the data published yearly by R. S. Means [5].

Given the damage state, that was described by the physical damage ratios obtained in the previous section, the next step is the calculation of repair cost. This is achieved by developing a repair strategy for each damage state and building type. Five damage states of negligible, slight, moderate, extensive and complete were used. In the case of a reinforced concrete column, for example, if damage is negligible or slight with minor deformations in connections or hairline cracks in a few welds, the recommended action may be a minimal repair or even to do nothing and, hence, the repair cost itself is negligible or zero. There may be alternative methods of repair, each associated with a different cost; the appropriate method may depend on the degree of damage and accessibility. At high levels of damage, replacing the affected member may be considered. (Note that the cost of replacing a damaged component may be as much as two times higher than the cost of the original placement. The “cost of replacing” should therefore not be confused with “replacement cost” as used in insurance terminology.)

The cost of repair also depends on the story on which the damaged component resides. In the case of a moment resisting frame building, interstory drift and, therefore, deformation, damage and the cost of repair are all higher at higher stories. Reinforcing this relationship, the conveyance of tools and materials to upper stories may be hampered by damage to lower stories or the lack of an operating elevator, thus, again, making repairs at higher stories more expensive.

Other costs including the cost of inspections, set up costs, demolition and removal of debris are also considered. Economies of scale exist, too; that is, the average per unit cost of small jobs will be higher than that of large jobs, as the fixed costs are spread over a larger volume. Correlation between cost of repair must also be taken into account. A given contractor may be equipped to perform repairs on a number of different component types. But a contractor hired to repair beams and columns is unlikely to perform repairs on dry wall, or electrical equipment. As the number of contractors goes up, so, too, do costs.

4.5 Final Damage Functions

So far, given the intensity of earthquake, described by spectral displacements, calculation of building deformations, component damages and finally replacement costs has been described. However, the analysis has been for a single case. In order to incorporate the uncertainty, a Monte Carlo simulation has been performed. Initially, given the spectral displacement, a number of simulations were performed to calculate inter-story drift ratios. For each interstory drift ratio, a number of simulations were performed to calculate component damage ratios. Finally, same number of simulations were performed for each physical damage ratio to calculate repair cost. Figure 6 illustrates this procedure. As a result, a distribution of repair costs was obtained for each value of spectral displacement. Then one can produce a damage function by calculating mean damage ratios from the repair cost distributions. Figure 7 compares such damage functions developed for several construction types.

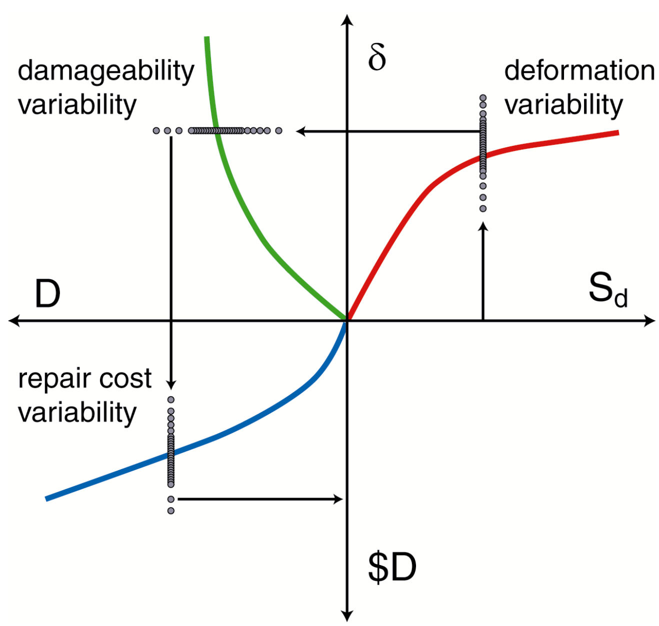

Figure 6: Illustration of the Monte Carlo simulation performed to obtain building damage functions

Conclusion

The advantages of ACM are many. Earthquake intensity is directly linked to individual building performance, rather than to ground shaking or the performance of the "average" building within a large portfolio of buildings. ACM captures the unique structural system of a building, as well as the seismic performance characteristics of its non-structural components. One implication of this is that damage patterns, as simulated by ACM, will much more closely resemble the pattern and spottiness of damage that is observed after actual earthquakes.

ACM damage functions are far more realistic than those of existing methods. Other damage functions treat buildings as a single, unified component, which is damaged smoothly and proportionally as it is subjected to increasing levels of intensity. But glass, for example, is not damaged smoothly. It undergoes stress until it breaks. While this example is perhaps extreme, most building elements and materials exhibit discontinuities in their capacity to withstand deformation. Because ACM models damage at the component level, it is able to capture such discontinuities.

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