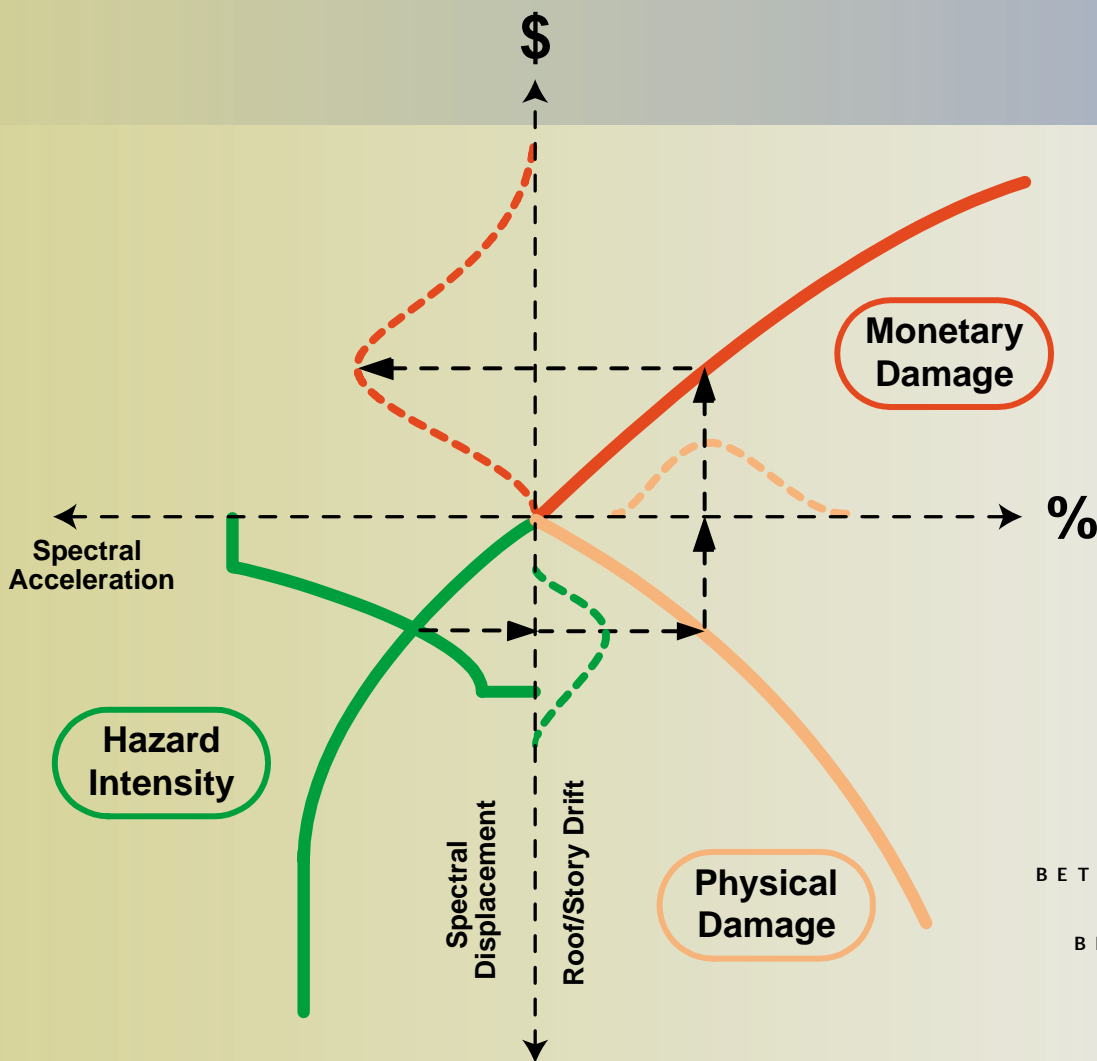


The Advanced
Component Method™

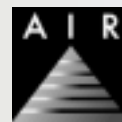
ACM

A Breakthrough in Vulnerability

Assessment Technology



BETTER TECHNOLOGY
BETTER DATA
BETTER DECISIONS



Introduction

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. The photograph below, taken in the course of AIR's field investigation of the 1999 Ji-Ji earthquake in Taiwan, illustrates this point. In it, one building is completely collapsed, another building has suffered only minor damage and a third — a temple built without the benefits of modern engineering or seismic code conformity — is entirely untouched.

The conventional approach to modeling building vulnerability to earthquakes, which typically uses Peak Ground Acceleration (PGA) and/or Modified Mercalli Intensity (MMI) as the measure of intensity, cannot fully capture this phenomenon. PGA does not reflect the full spectrum of frequencies of the seismic waves entering the site. These frequencies will resonate differently with different buildings, and will result in a wider dispersion of damage than can be captured by PGA or MMI alone.

In order to better model the phenomenon of diffuse and irregular damage patterns and to supply our clients with the most reliable loss estimates, AIR structural engineers launched an intensive R&D effort to develop an objective and more accurate methodology for assessing the vulnerability of specific buildings and their contents to earthquakes. This research effort has resulted in a dramatic new breakthrough technology: the Advanced Component Method, or ACM™.

ACM™ – The Next Step

The Advanced Component Method developed by AIR takes a significant step beyond both ATC-13 and HAZUS (see next page for a history of vulnerability assessment). With ACM, an objective and scientific methodology largely replaces the subjective measures and opinions of experts about how building damage relates to earthquake intensity. ACM is transparent. Because the underlying parameters are accessible and the significance of each is well understood, ACM can be calibrated. It can be extended to include new construction types, building practices and building codes.

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The spottiness of damage was strikingly evident in both the Ji-Ji and Izmit earthquakes. In this photograph, one modern building has completely collapsed, while others remain intact, including an old temple built without the benefit of seismic design.

Earthquake Vulnerability Assessment:

AN ABBREVIATED HISTORY

The science of vulnerability assessment, that is, of estimating the probability and extent of earthquake damage before an earthquake occurs, is quite young. It is only since the introduction of seismographic instruments that scientists and engineers have had access to sufficient information to attempt a quantitative description of the relationship between earthquake intensity and damage.

Information about earthquakes that predate the introduction of seismographs consists primarily of eyewitness accounts as documented in newspapers, letters, and journals of the time. Eventually, as an outgrowth of work by the 19th century Italian seismologist Giuseppe Mercalli, the twelve-point Modified Mercalli Intensity (MMI) scale was introduced in 1931. Its purpose was to classify the intensity of historical earthquakes by mapping geographically the descriptive information in these written, historical accounts. MMI is a "qualitative" assessment of earthquake intensity. Its "measurements" are based on subjective human responses to ground motion and on observed damage.

Most recent attempts to assess building vulnerability to earthquakes have been based on observations made in the aftermath of earthquakes and on the opinion of experts as to the potential impact of an earthquake.

ATC-13 One of the first systematic attempts to codify 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 (CA. 1985), which was funded by the Federal Emergency Management Agency (FEMA). ATC-13 essentially derived damage functions by asking experts—noted structural engineers, builders and the like—to estimate the expected percentage of damage that would result to a typical building of a specific construction type were that building 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. Fifty-eight experts were assembled and polled; in some cases, however, only a handful felt themselves sufficiently expert with respect to a particular structural type to venture an opinion.

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.

The primary drawback to the ATC-13 approach, however, is its subjectivity. ATC-13 damage functions are based exclusively on the subjective opinion of experts. For this reason, they are difficult to calibrate or modify in order to incorporate new data or technologies. Suppose, for example, that a new seismic code is implemented. How does one go about modifying the ATC-13 damage functions? What parameters should be changed and by how much?

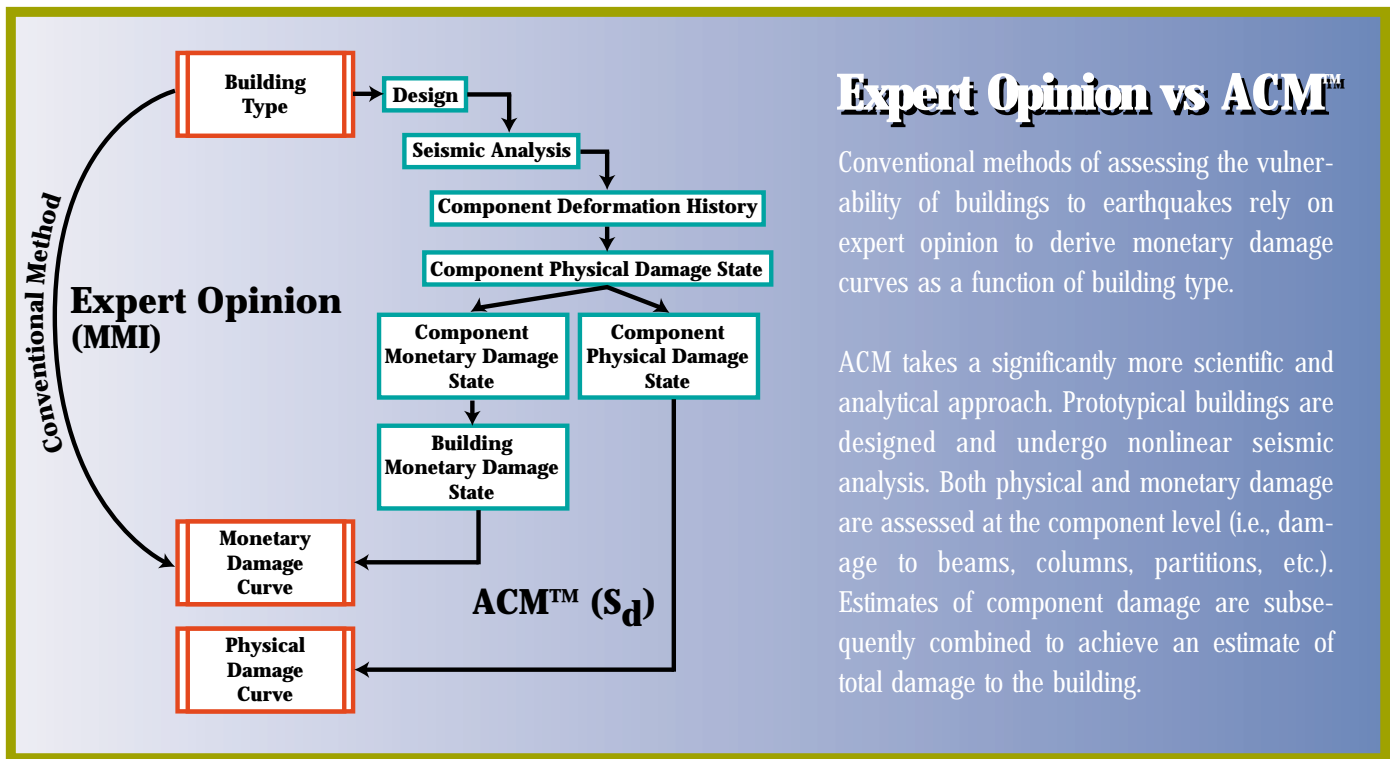
How does one extend ATC-13 to other building types, other regions, or to individual building characteristics? Furthermore, while uncertainty is inherent to any estimation of damage due to the variability in actual building performance, the uncertainty surrounding ATC-13 damage functions is that of the experts regarding their own opinions.

HAZUS A second major effort to develop a methodology for vulnerability assessment was undertaken by the National Institute of Building Sciences (NIBS), and funded again by FEMA. The result, HAZUS, was released in 1997 as a risk assessment interactive software, well documented in three volumes (FEMA, USA, 1997). HAZUS replaced ATC-13 as the then state-of-the-art methodology for vulnerability assessment.

In HAZUS, spectral displacement (S_d) and spectral acceleration (S_a) 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 judgment to estimate the state of damage that would result from a given spectral displacement and acceleration. While HAZUS represents a significant advance, the difficulties surrounding reliance on expert opinion remain.

It can be updated as repair costs change and new repair strategies are introduced. ACM is based on sound, quantifiable scientific and engineering principles

and has undergone extensive validation and testing by comparing model results with data from both actual historical events and from experimental observations.

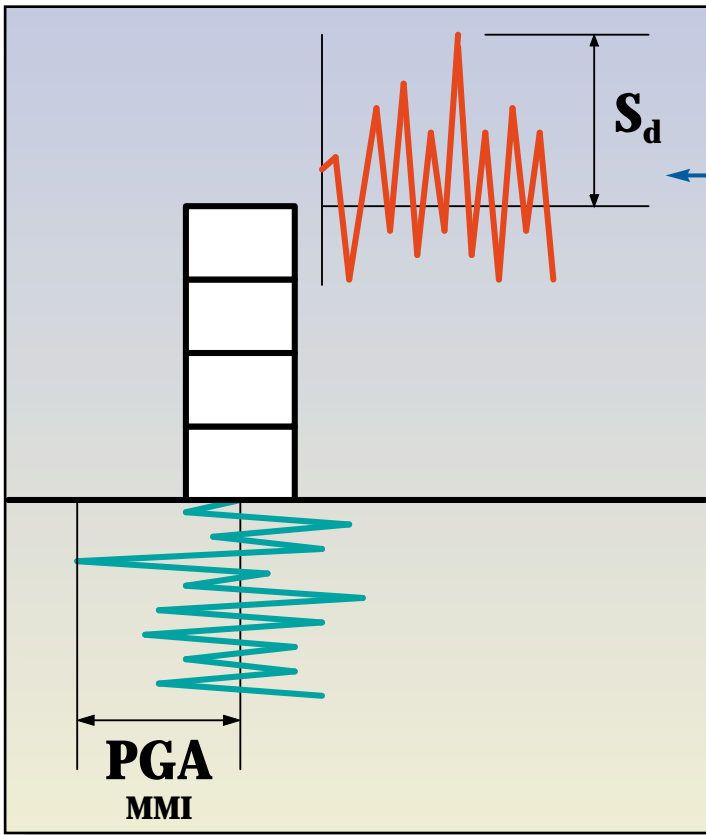


An Objective Measure of Intensity

An objective methodology for assessing building vulnerability must begin with an objective measure of intensity. Until recently, the most commonly used measure of intensity was MMI. Another common measure is peak ground acceleration (PGA), which is subsequently translated into a functional variant of MMI. The problem with MMI is its subjectivity. The primary problem with using PGA is that, although objective, it is a measure of ground motion and not a measure of how buildings respond to ground motion. Put another way, using PGA and,

indirectly, MMI as a measure of intensity assumes that, during an earthquake, the top of a building moves exactly in unison with the bottom of the building, that is, like the ground itself. This ignores any effect of a building's natural period (which is a function of its flexibility and mass), or of the resonance between the building's motion and ground motion.

AIR engineers selected spectral displacement, S_d , as an objective measure of intensity. S_d is the maximum horizontal displacement experienced by a building during an earthquake. When displacement occurs, the building and its component parts are deformed; deformation causes damage. In ACM, damage depends not



Traditionally, maximum ground acceleration was the measure of building damage. ACM shifts the focus away from ground motion and toward building deformation as the measure of intensity — and therefore of damage.

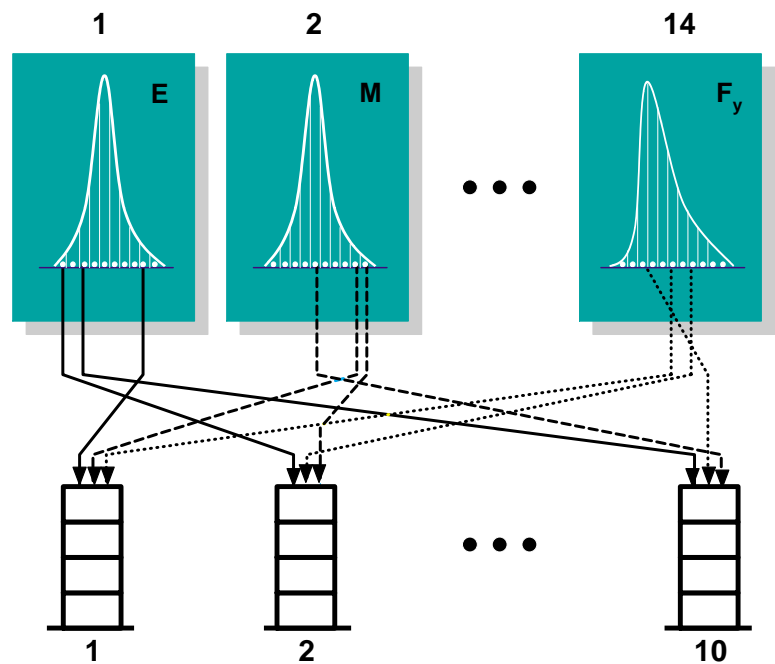
on how the ground is shaking, but rather on the deformation response of individual structural and nonstructural components to ground motion. Because each building has different mechanical characteristics and a different natural period, each will be subjected to a different seismic intensity (spectral displacement) and, hence, a different damage state.

The Identification and Design of Typical Buildings

AIR engineers first identify buildings typical of the modeled region and define their general configuration and characteristics. Local design firms are enlisted to ensure conformity with local and regional construction practices.

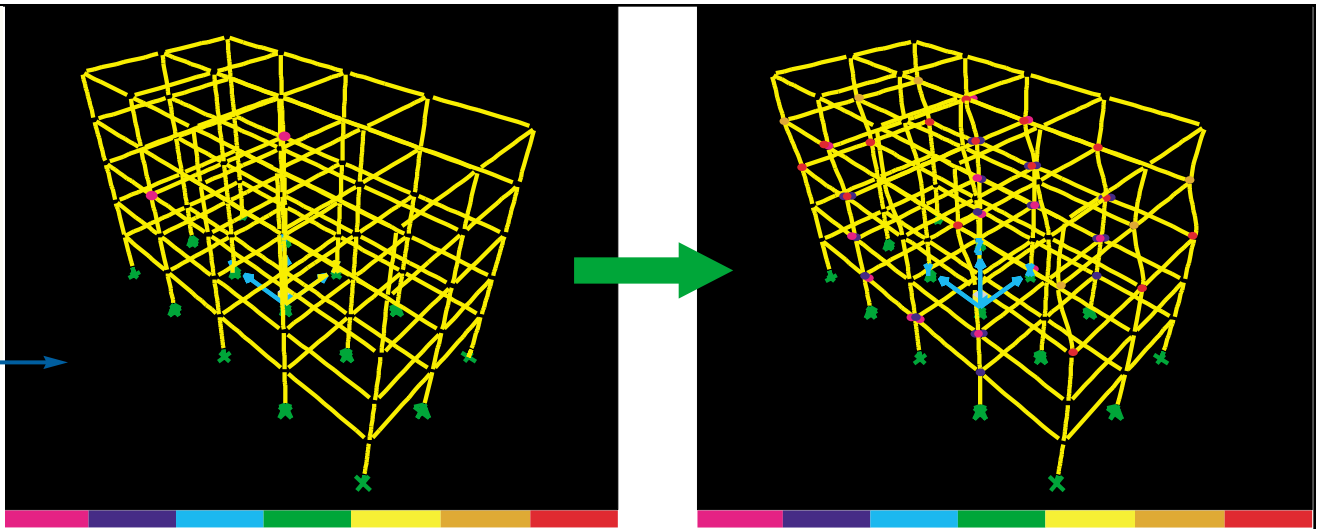
Actual design plans are created for each building type. Design documents include the physical dimensions of each component, as well as their axial, bending, moment and shear capacities, yield strength and other material properties. Each building type is to be as representative of the average in the modeled region as possible.

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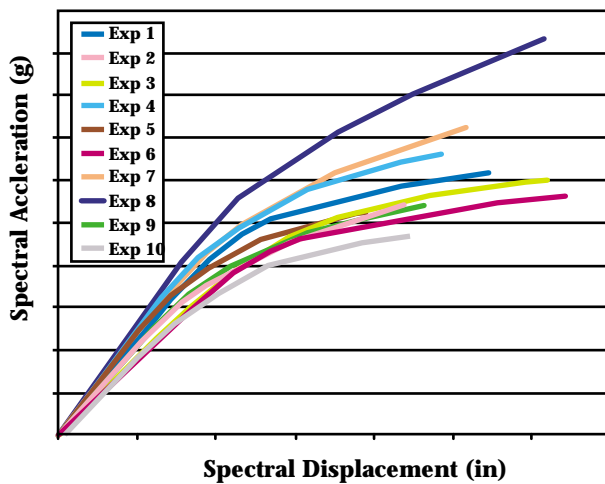


Using Latin Hypercube sampling techniques, ACM captures the variability in building characteristics and loading and, therefore, in buildings' response to ground motion.

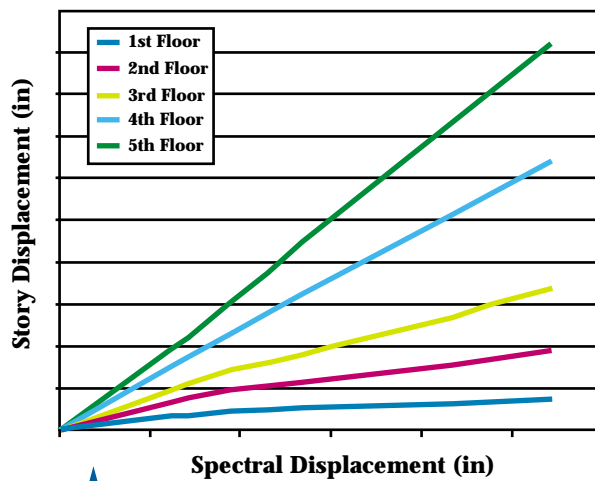
Seismic (Pushover) Analysis. As individual elements fail, force is redistributed to the elements that remain intact.



X-Direction Capacity Curve



X-Direction Displacement



Out of the nonlinear seismic analysis come capacity curves and floor deformation histories, thus capturing variability in building response to the chosen earthquake intensity, i.e., spectral displacement. Note that, as the figure above implies, pushover is performed in two directions. Deformation occurs as components are displaced in the x or y direction or are rotated, as in the case of torsion.

Nonlinear Seismic Analysis

Various analytical methods are available for modeling the effects of earthquakes on an individual building. AIR

engineers selected a nonlinear seismic analysis procedure and performed the analysis using SAP2000, a highly reliable and widely used commercial software application.

Three-dimensional models of each building, expressed mathematically, are input into the software. Ground motion is modeled as the application of lateral load, which monotonically increases over the height of the building. The amount of load applied is the amount required to horizontally displace, by fixed amounts, each and every floor of the building. This process is repeated, with incremental displacements, until the building collapses. At each stage, lateral force is distributed to the nodes, or joints, where beams and columns connect. As joints and members fail, the force is redistributed to the elements that remain functional. Lateral forces are applied in two directions, separately, and the effects are combined to achieve a three-dimensional analysis that captures the building's dominant modes of vibration and approximates the results of a time history analysis.

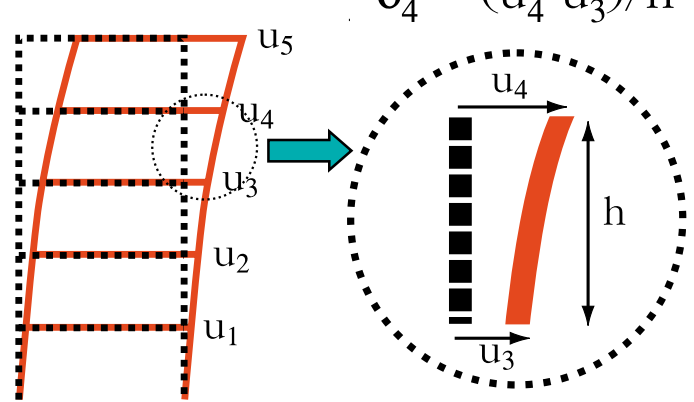
Damage Analysis

Physical Damage

The ACM approach to the estimation of damage at the component level necessitates the "decomposition" of the building into its component parts. Experimental data, as documented in dozens of studies published in refereed journals, are used to estimate damage to each of a building's components as they undergo deformation.

The mean damage ratio to the individual component is calculated and, around each mean, a complete probability distribution is estimated.

To combine the damage to all components of a given type, a weighting mechanism was developed based on published engineering studies, such that the importance of each component to total building damage is a function of the story on which that component resides.

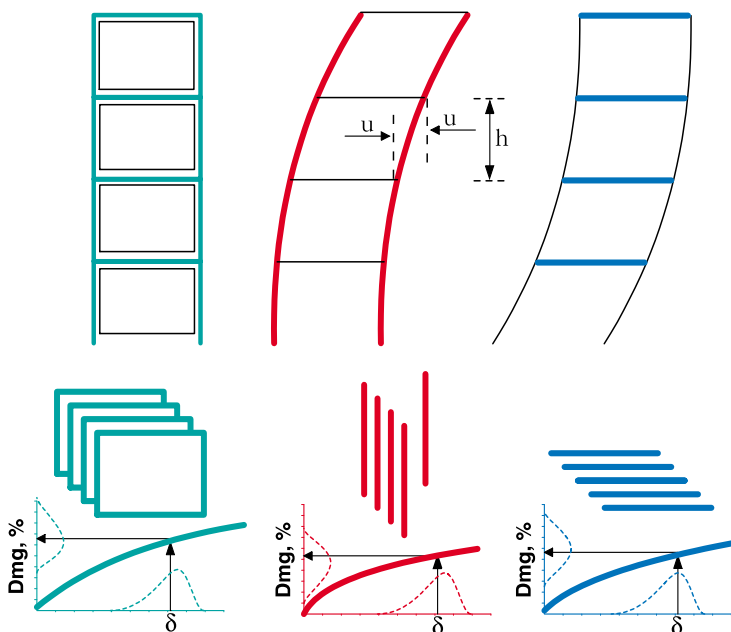


Once the damage ratios for each component type are estimated, they are combined to achieve a total building damage ratio. A combined damage function for all structural components is estimated using weights based on the relative importance of each component type to system performance. For example, in the case of steel moment resisting frame, beams and columns receive a higher weight than floors. Separately, a damage function for nonstructural components, including partitions, cladding, glazing, suspended ceilings and MEP (mechanical, electrical, plumbing), is estimated.

Damage functions are developed separately for structural and nonstructural components because different occupancy types will exhibit different proportions of structural and non structural elements. For example, a hospital and a parking garage may have very similar structural systems and structural components. Their non-structural components, however, differ dramatically.

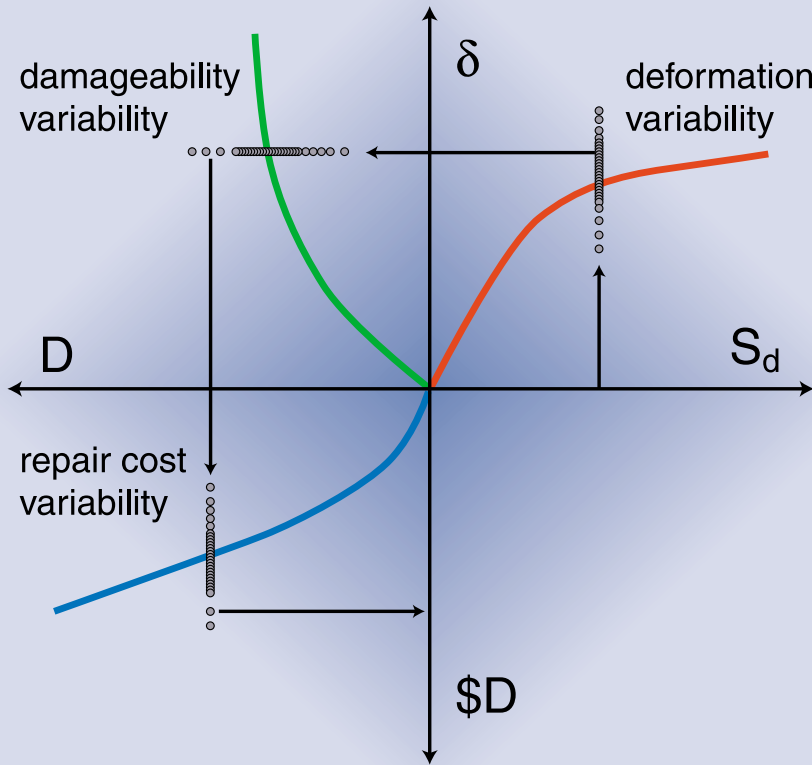
Monetary Damage

Traditionally, catastrophe modelers have estimated monetary damage either by way of ATC-13 curves, which are based on expert opinion, or by multiplying HAZUS physical damage ratios by the replacement cost of the building. ACM estimates monetary damage at the micro, or component, level and the component damages are subsequently aggregated to produce building monetary damage curves.



Damage functions are developed for each component type, both structural and nonstructural.

Incorporation of uncertainty. For each random variable (material properties, loads, repair costs, etc.), a large number of samples are generated using stochastic simulation techniques, resulting in one million sample points for each level of spectral displacement.



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.

Repair costs are determined by identifying the repair strategies for each damaged component on each floor of the building, given their physical damage state. The cost of inspections, set up costs, demolition and removal of debris are also included.

For the development of a comprehensive cost model for assessing earthquake damage to buildings, AIR engaged the services of experts from the Department of Civil and Environmental Engineering at Northeastern University.

The state-of-the-art model estimates the cost of repair for each damaged component (beam, column, floor, etc.). Repair cost depends on repair strategy, which depends, in turn, on the physical damage state of each component. 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 at all. Hence, the repair cost, in this instance, is negligible or zero. There may be alternative methods of repair, each

The repair costs of each individual component are combined to achieve an estimate of the monetary damage, or cost of repair, to the building as a whole. Using R. S. Means data on buildings, a monetary damage ratio is produced. This ratio, plotted against intensity, or spectral displacement, represents the monetary damage curve. Note that the total estimated cost of repair may sometimes exceed the replacement cost of the building. In this case, replacement cost is used as a cap to the estimate of monetary damage.

The use of hard data on repair and replacement cost guarantees that the model can be updated every year using the most current cost information available.

Calibration and Validation

ACM physical and monetary damage curves have been calibrated and validated using data on building performance obtained from various sources, including experimental data from universities and research laboratories, and post-event observation data on both single sites and portfolios of buildings. Single site data is also collected from published studies, as well as from post-disaster field investigations, such as those performed by AIR engineers. Portfolio data is provided by the insurance industry and by various federal, state and local governmental agencies.

AIR engineers analyzed and translated the data in order to make comparisons with ACM results meaningful. Sources of bias were eliminated. Before data were used for calibration, they were normalized for the peculiarities, or individuality, of each historical event. ACM damage functions were compared to existing benchmark damage functions such as ATC-13, HAZUS and those of AIR's current production model. A careful analysis revealed that the differences were those that AIR engineers had anticipated.

ACM damage functions underwent an exhaustive process of review, validation, and calibration at every state of their development. Results show a good correspondence between modeled and observed damage.

MIT Professor Robert Whitman has high praise for ACM™

ACM has been externally reviewed by Dr. Robert Whitman, Professor of Civil Engineering at the Massachusetts Institute of Technology (MIT). Professor Whitman was involved in one of the earliest efforts to develop damage functions for earthquake and has spent much of his career in the development of earthquake loss estimation methodologies. Most recently, he was Chairman of the Project Work Group for HAZUS. Professor Whitman writes in his report on ACM:

“I am very impressed with what has been and is being done.” He goes on to say, “It is important that buildings are being examined in more detail using pushover curves for actual designs, that a more detailed look is taken at the potential costs of damage, and that there be a systematic effort to quantify the uncertainty in estimated losses. I hope that someday the entire loss estimation community will be able to benefit from what you are doing...”

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 nonstructural 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 as a result of actual earthquakes.

ACM damage functions are far more realistic than those of other modelers. 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 brittle nonstructural materials such as glass, for example, are not damaged smoothly. They undergo stress until they break. Most building elements and materials exhibit discontinuities in their capacity

to withstand deformation. Because ACM models damage at the micro, or component, level, it is able to capture such discontinuities. The focus of ACM is on the response of individual buildings to earthquake intensity, so truly objective site-specific analyses can be performed that will produce far more reliable results than previously available.

ACM damage functions have been calibrated and validated against historical damage observations, actual loss data, and carefully conducted experiments.

The Advanced Component Method developed by AIR represents a major advance over all other existing approaches to assessing and modeling building vulnerability to earthquake.



Acknowledgments

Research Engineers:

Dr. Nozar G. Kishi, Manager of Engineering Research at AIR, was Project Manager for ACM and oversaw its development and implementation.

Dr. Richard Song, Senior Research Engineer at AIR, had primary responsibility for the structural design and seismic analysis of buildings for ACM.

Dr. Ugur Kadakal, Senior Research Engineer at AIR, conducted the damage aggregation of structural and nonstructural elements at both the component and building level.

Dr. Ji-Seok Byeon, Research Engineer at AIR, compared ACM damage functions with observed damage data and performed validation procedures.

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