Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 480

FRAGILITY OF NON-STRUCTURAL COMPONENTS FOR FEMA BENEFIT COST ANALYSIS

John M. Eidinger[1]

ABSTRACT

This paper provides 54 seismic fragility functions for 15 classes of non-structural components found in common industrial, commercial, government and residential facilities. The fragility functions are meant to be used for considering cost-effectiveness when doing benefit cost analyses under the FEMA Pre-Disaster Mitigation Program or similar activities, or loss modeling over large populations. Application of fragility models for performance based design of specific facilities is discussed.

Introduction

The U.S. Federal Emergency Management Agency provides various grant programs for applicants to obtain (usually) about 75% co-funding for earthquake mitigation projects. In order to be eligible for FEMA co-funding, each project must be shown to be *cost-effective*. To be cost-effective, the applicant must demonstrate that the accrued *benefits* of the project outweigh its *costs*; in other words, the *benefit-cost-ratio (BCR)* must be 1 or larger.

A benefit cost analysis (BCA) is used to compute the BCR. The calculation of the BCR requires the applicant to quantify the costs and the benefits of the project. The computation of the benefits involves assumptions about the annual probability of various size earthquakes, and, given the occurrence of various size earthquakes, the impacts (direct damage and direct economic losses) should the item (building, equipment, pipeline, etc.) be damaged. FEMA (2006) provides specific guidance as to how this analysis should be performed.

The FEMA software for non-structural component evaluations includes a number of "default" fragility curves (Table 2). It is FEMA's normal policy that if the applicant uses the default fragility models, that no further justification is required. Up until 2009, FEMA always allowed the applicant to replace the "default" fragility models with user-defined project-specific models; this makes good technical sense, in that project-specific installations might have different characteristics than the "default" fragility models. FEMA also has a desire to provide a "level playing field" for all applicants, so FEMA discourages project-specific fragility models as there could be "unfair advantage" obtained by some applicants, or possibly, intent to "game the system" by using improperly substantiated fragility and hazard models.

---

[1] Principal, G&E Engineering Systems, eidinger@geEngineeringSystems.com, Olympic Valley, CA 96146-3592

Fragility Models

The FEMA documentation does not provide the user with details as to how the default fragility models were prepared, or when they are applicable. This can confound the applicant (as well as the FEMA reviewer) in that they cannot easily establish when the default FEMA fragility models are (or are not) applicable to a particular situation at hand. As an outgrowth of the ATC 58-2 effort, a report (Eidinger, 2009) was prepared that describes the technical reports, test data, analyses and empirical evidence and judgment used to prepare fragility models for non-structural components, see Table 1. The following describes the columns.

Damage state. This is a text description of the damage state. See (Eidinger, 2009) for examples.

Median A (g). This is the median input level zero period acceleration (ZPA) level to the equipment needed such that 50% of a "sort of homogeneous" population of these items will reach this damage state. Except as noted, the input-level ZPA is the peak horizontal ground acceleration (PGA, geometric mean of two directions) for items subjected to the free-field motion. The input ZPA is almost always lower than the PGA for items at sub-grade basement levels, and often higher (not always) for items placed at higher floors in a multi-story structure. For items in basements or at elevated floors (especially penthouses), the user must adjust the free field motion to reflect the median motion for the floor in question.

Beta total. This is the combined lognormal standard deviation (dispersion parameter) to be applied to the median A, assuming a magnitude 6.5 to 7 earthquake on a crustal fault in California. For coastal Oregon, Washington and Alaska, where magnitude 8+ subduction zone earthquakes dominate the seismic hazard, a larger uncertainty occurs in forecasting the level of motion, as compared to that in most of California. The column "Beta Equipment" is provided which provides the dispersion *only* for the equipment. This implies that (beta total) = square root (beta**2 (ground motion) + beta**2(equipment)). For sites subject to subduction zones, it is recommended that beta (ground motion) should be at least 0.60, making beta (total) at least 0.67. If the user has the ability to quantify beta (ground) for a specific site, then it is recommended that "beta equipment" be combined with the beta (ground, site specific) instead of using "beta total". The FEMA BCA software does not readily allow the user to alter the beta values, so for FEMA application, the "beta total" value can be used as a first order approximation.
Notes. Short notes describing the type of equipment being considered.

Before and After Mitigation – the Case of a Piece of Mechanical Equipment

When performing a BCA, one needs both the "as-is" and "after seismic mitigation" fragility values for each component being considered for possible seismic mitigation. While the Engineer might tell the Owner that the upgrade will make the item "seismic proof", this statement is a gross simplification in most practical installations in commercial structures. For example, when one adds anchorage to a piece of mechanical equipment (say a lathe in a machine shop), the anchorage is designed for (perhaps) a factor of safety of 1.5 (after considering "magic" R and the factor of safety against ultimate failure of the anchor bolt), designed to say PGA = 0.40g. The

Table 1. Fragility Models (2009)

Damage State	Median A (g)	Beta Total	Beta Equipment	Notes
Suspended Ceilings - moderate damage	0.50	0.50	0.30	Wire hung
Suspended Ceilings - extensive damage	0.90	0.50	0.30	Wire hung
Suspended Ceilings - moderate damage	0.80	0.50	0.30	Add compression struts
Suspended Ceilings - extensive damage	1.30	0.50	0.30	Add compression struts
Elevators – Generic	0.40	0.50	0.30	
Elevators – No seismic design	0.35	0.50	0.30	
Elevators – With seismic design	0.90	0.50	0.30	
Raised Floors – No Seismic Design	0.50	0.60	0.45	
Raised Floors – Limited Seismic Design	0.70	0.60	0.45	
Raised Floors – Basic Seismic Design	1.50	0.50	0.30	
Raised Floors – Full Seismic Design	3.00	0.50	0.30	
HVAC Ductwork - Building - extensive Damage	1.25	0.54	0.36	Rod hung
HVAC Ductwork - Building - complete Damage	1.88	0.54	0.36	Rod hung
HVAC Ductwork - Building - extensive Damage	2.38	0.54	0.36	With sway braces
HVAC Ductwork - Building - complete Damage	3.00	0.54	0.36	With sway braces
HVAC Ductwork - Penthouse - extensive Damage	0.50	0.54	0.36	Rod hung
HVAC Ductwork - Penthouse - complete Damage	0.75	0.54	0.36	Rod hung
HVAC Ductwork - Penthouse - extensive Damage	0.96	0.54	0.36	With sway braces
HVAC Ductwork - Penthouse - complete Damage	1.50	0.54	0.36	With sway braces
HVAC Vibration-isolated rotating equipment	0.50	0.50	0.30	No seismic design
HVAC Vibration-isolated rotating equipment	1.50	0.50	0.30	With seismic design
Bottom heavy equipment items	0.75	0.50	0.30	Unanchored
Evenly weighted equipment items	0.60	0.50	0.30	Unanchored
Top heavy equipment items	0.40	0.60	0.45	Unanchored
Bottom heavy equipment items	0.90	0.50	0.30	Poorly anchored
Evenly weighted equipment items	0.75	0.50	0.30	Poorly anchored
Top heavy equipment items	0.50	0.60	0.45	Poorly anchored
Well anchored equipment items	1.50	0.50	0.30	Standard anchors
Pendant Light, non-seismic	0.60	0.50	0.30	
Pendant Light, with restrainer clips	1.10	0.50	0.30	
Pendant Light, seismic design	1.50	0.50	0.30	
Rigid Block, W/H = 0.33, unanchored	0.60	0.50	0.30	Toppling
Rigid Block, W/H = 0.33, common anchorage	1.50	0.50	0.30	Toppling
Rigid Block, W/H = 0.33, heavy anchorage	3.00	0.50	0.30	Toppling
Office workstation	1.00	0.50	0.30	Unanchored
Diesel Generators – seismically qualified	1.10	0.50	0.30	
Diesel Generators - well anchored	0.60	0.50	0.30	Higher if in daily use
Diesel Generators - seismically vulnerable	0.25	0.60	0.45	Higher if in daily use
Electrical Cabinet - Unanchored	0.60	0.60	0.45	
Electrical Cabinet - Nominally Anchored	1.00	0.60	0.45	
Electrical Cabinet - Well Anchored	3.00	0.60	0.45	
Communication Rack – Unanchored	0.20	0.60	0.45	

Damage State	Median A (g)	Beta Total	Beta Equipment	Notes
Communication Rack - Flexible	1.00	0.60	0.45	
Communication Rack – Well anchored	1.50	0.60	0.45	
Top heavy equipment on rollers	0.40	0.50	0.30	Rolling
Top heavy equipment on rollers	0.60	0.50	0.30	Toppling
Mechanical equipment, no anchorage	0.60	0.60	0.45	Breaks attached pipes
Mechanical equipment, light anchorage	0.70	0.50	0.30	
Mechanical equipment, heavy anchorage	2.00	0.50	0.30	
Storage Rack – Loose items slide to floor	0.30	0.60	0.45	
Storage Rack – Pallets slide to floor	0.70	0.60	0.45	
Storage Rack – 27-11 design, Collapse, W < 0.40	0.90	0.50	0.30	
Storage Rack – 27-11 design, Collapse, W > 0.60	0.60	0.50	0.30	
Storage Rack – High seismic design, Collapse	1.50	0.50	0.30	

upgrade does not address damage that might still occur if: the anchor bolt is not installed properly; it is damaged over years of use; the earthquake ground motion is larger than PGA = 0.40g, and all other damage modes possible for the lathe. For example, in Table 1 an unanchored piece of mechanical equipment has A, b = (0.60g, 0.60), whereas an lightly anchored version as A, b = (0.70, 0.50), whereas a heavily anchored version has A, b = (2.00, 0.50). Note that light anchorage (say two 0.25-inch diameter bolts for a 4 ton piece of equipment) is grossly overloaded for large ground motions. For this example, the median value for "heavy anchorage" is a quite robust 2.00g, which for all practical purposes, eliminates this damage state.

The user might question: how did "2.00g" get selected, and is it applicable to the specific anchorage for a specific piece of equipment? This question is an excellent one, and gets to the "heart" of how these fragilities curves should be used. The answer is as follows:

- First, the 2.00g is applicable only to a large group of similar pieces of equipment. If the user has a specific design for a specific piece of equipment in mind, then the user should always override the "default" 2.00g and replace it with the equipment-specific application. In other words, the author has no knowledge of whether the new anchorage will use 4 – 0.5-inch diameter bolts with 4 inch embedment in 3,000 psi concrete; or 6 0.75-inch diameter bolts with 6-inch embedment placed in 5,000 psi concrete.

- Second, the author has no knowledge of whether the anchorage installation will factor in prying effects, edge distance effects, quality of installation, for any specific planned installation.

- Third, if the median were set to 3.00 g, in almost all cases, the decision to anchor / not anchor would be the same, as the probability of failure for the equipment (2.0, 0.5) or (3.0, 0.5) is not too dissimilar in absolute sense for most practical cases.

- To summarize. The 2.00g fragility should NOT be used for a specific installation, even though this is common practice and a de-facto requirement in the FEMA BCA software.

Well, is this acceptable practice? For purposes of obtaining FEMA co-funding for anchoring equipment at a University biology laboratory, it certainly seems to be. On the other hand, if the application were the safety of the reactor vessel in a nuclear power plant, it is not acceptable practice.

What About the Shape of the Distribution

The typical user of FEMA BCA software accepts that the lognormal distribution has some physical meaning and is "correct" for purposes of BCA. The reality is that the lognormal distribution was selected mostly for mathematical convenience. So, why do we use it?

The bottom line reason that the lognormal distribution is used for earthquake loss estimation is that A(failure) = A(median)*exp(x*beta), where x = the number of standard deviations, and this formula always produces a positive result. If we were to use the normal distribution, A(failure) can be predicted to be negative, a clearly illogical result. At the heart of the matter are the following issues:

- First. The inventory of observed damaged components (from past earthquake or from test) is still very small. In almost all cases, there is no homogeneity in the observed sample sets. By "homogeneity", we mean that statisticians require a large sample (often 60 or more identical items) in order to have a high confidence of the predicted outcome. Well, we can say with confidence that in the real world, we almost never have 60 identical items exposed to earthquakes.

- Second. While there are now a few privately-developed datasets of more than several thousand non-structural components exposed to real-earthquakes, the underlying data in these sets (usually a photo, rarely floor level within a building, almost never the original drawings) is simply too imprecise to meet the statistical requirements. For example, we might use a dataset to get a median fragility level for "anchored" or "unanchored" equipment, but we cannot use the dataset to quantify the anchorage by: depth of embedment; strength of concrete; diameter of bolt; edge distance effects; prying effects; height, width, mass, center of mass, or rigidity of the equipment.

FEMA Default Fragility Models

Table 2 lists the median fragility level for a variety of equipment, as incorporated in the FEMA BCA software. These were based on empirical evidence, test data and judgment available to the author as of 2003. The updated fragility models (Table 1) incorporate six additional years of data collection from real-world earthquakes, and newer laboratory test data. For the most part, the changes in 2009 from 2003 are modest.

Table 2. Fragility Models (2003)

Item	FEMA A As Is	FEMA A Upgraded
Generic bottom weight unanchored	0.75	1.50
Generic bottom weight poor anchored	0.88	1.50
Generic even weight unanchored	0.60	1.50
Generic even weight poor anchored	0.73	1.50
Generic top weight unanchored	0.40	1.50
Generic top weight poor anchored	0.49	1.50
Parapet walls URM extensive damage	0.40	1.10
Parapet walls URM complete damage	0.60	1.50
Racks – shelves	0.60	1.00
Generators on isolators	0.25	0.60
Elevators moderate	0.35	0.90
Elevators extensive	0.75	1.50
Fire sprinklers limited	0.25	0.52
Fire sprinklers widespread	0.50	1.00
Fire sprinklers extensive	0.75	1.50
HVAC fans	0.30	1.00
HVAC ductwork rod hung extensive	1.25	2.38
HVAC ductwork rod hung complete	1.88	3.00
HVAC ductwork rod hung in penthouse extensive	0.50	0.96
HVAC ductwork rod hung in penthouse complete	0.75	1.50
Suspended ceiling wire hung moderate	0.25	1.50
Suspended ceiling wire hung extensive	0.50	>1.50
Suspended ceiling wire diagonals moderate	0.50	1.50
Suspended ceiling wire diagonals extensive	0.90	>1.50
Suspended ceiling comp struts moderate	0.80	1.50
Suspended ceiling comp struts extensive	1.30	>1.50
Electrical cabinets unanchored	0.60	3.00
Electrical cabinets poorly anchored	1.00	3.00

Inventory Issues

One way to address the inventory for an existing building is for the cognizant engineer to perform a field survey of all the equipment and note its style of construction. This effort would ideally include review of original specifications, knowledge of actual construction, knowledge of actual material properties, etc.

For new construction, it *should* be entirely within the engineer's purview to specify the type of equipment that should be installed, as well as all the corresponding seismic details. Developing such detailed specifications will require additional time and effort on the part of the engineer, and possible additional cost during procurement.

Some owners may balk at having to pay for the extra effort to develop accurate inventories and detailed design of non-structural components, especially if it is over and beyond code minimum. In such cases, it is entirely proper for the engineer to tell the owner that "you get what you pay for" and the engineer should warn the owner that the building / equipment may fail to perform reliably under the design-basis earthquake. In other words, the proper application of seismic design for many types of non-structural components should not be construed as being a "customary" level of service on the part of the engineer, unless the engineer is charged with developing a code certification report for each component. Industry documents such as those by NFPA, SMACNA, CISCA and similar, where "install-by-rule" provisions are made for seismic loads, should not be construed as providing functional reliability. Lacking such a level of effort, the engineer is not in responsible charge for seismic design for functionality of non-structural components.

If the engineer is not aware of the actual inventory of equipment in a building, then it is very likely that the fragility information in Tables 1 or 2 will be mis-used. For example, if the engineer does not know whether or not a piece of equipment is anchored, then the engineer cannot use the fragility information in this paper. Eidinger (2009) provides descriptions of damage to various types of equipment and components in past earthquakes, test programs, engineering judgment, with consequences on life safety, function and repair, all of which enters into the formulation of the fragility models. To correctly apply the fragility models, one needs to understand the assumptions inherent in their development, which often times implies knowledge of the inventory of what was damaged in past earthquakes (or shake table tests, etc.) and how that is relevant to the actual inventory of equipment / components being evaluated in an actual building. Any mis-match in actual inventory assumptions and fragility models presented in this paper will result in errors.

Importance I and Magic R

In comparing code based design issued to qualification using fragility models, one may need to address the code factors for importance I, and magic R. I refers to the code's attempt to reduce the level of damage between regular ($I = 1$), important ($I = 1.25$) and essential ($I = 1.5$) facilities. Say we assume that the ground hazard beta is 0.40 (common in California). In other words, as $\exp(1 * 0.40) \sim 1.50$, then by selecting $I = 1.50$ we are reducing the scenario chance of exceedance at a particular PGA level from about 50% to about 16%.

Magic R refers to the "response modification coefficient" for non-structural components, sometimes called Rp in some codes. It is currently commonly set at R (or Rp) = 3 for many non-structural components; in older codes, as high as 8. The authorship of the codes (UBC, IBC and their predecessors) appear to have "pulled Rp out of a hat", largely with the intent to not increase the cost of construction for regular buildings over and above historical norms; and with some thought that "steel anchor bolts" are "ductile". As of 2009, it is evident that code-based seismic design of certain kinds of non-structural components (such as elevators) have failed to perform with hoped-for good performance in past earthquakes: available evidence suggests that perhaps more than half of all elevators suffered structural damage that required repairs, in the 1994 Northridge earthquake, in areas exposed to PGA ≥ 0.40g. The ASME code does not allow for "R" reduction factors when using simple code rules to qualify equipment. Operability issues for some types of equipment require them to remain elastic in order for tight-tolerance components to work. In this regard, one can justify the code-base R value for anchorage, *only if* one also designs the anchorage with a factor of safety of about 3 or 4, and *only if* the equipment is seismically more robust than its anchorage system. In other words, good anchorage performance occurs when the Seismic Demand (code computed with R=3, or one-third of elastic forces) remains less than the Seismic Capacity (set at 25% of average ultimate capacity), so that the real demand remains somewhat under real capacity; and allowing that modest overload of an anchorage system does not always lead to toppling (or severe sliding and breakage of attached commodities) of the piece of equipment. The "magic R" values are further confounded by the sometimes bizarre seismic design code approaches (design-by-rule) used for adding lateral braces for commodities, which are addressed in the next section.

It is recommended that for *new* construction, that the Engineer design standard anchorage systems for non-structural equipment using the code approach (recognizing that the code has little technical merit behind R), as well as using a performance based approach for essential facilities. In most cases, using 0.75-inch diameter bolts when the code requires only 0.5-inch diameter bolts, is an inconsequential additional expense for new construction.

For seismic retrofit of existing non-structural components, there is generally no need to meet the code rules for new construction in the evaluation stage; therefore the Engineer can use performance based design to consider how many non-structural items are truly at risk, and then work with the Owner to define an acceptable level of risk for the project at hand. Finally, for specific components ultimately selected for upgrade, the Engineer can follow the minimum of new code requirements or performance based design, based on an agreement with the Owner.

Commodity Issues

Commodities include above ground pipes, conduits, cable trays and HVAC ducts. Earthquake restraints (lateral bracing) for these commodities, as determined by the UBC, CBC, IBC and ASCE 7 codes and other industry guidance such as SMACNA, are oriented to reducing life safety risk, by limiting the falling potential for these items. Post earthquake functionality of these commodities is *not* assured by following the these codes or guidelines, and in some cases, the code-mandated lateral brace support systems (where specified by install-by-rule) may increase the potential for functional failure of the commodity.

For life safety, there is almost never a need to add lateral braces. Rod-hung commodities have an extremely high success rate in past earthquakes for providing adequate life safety resistance (i.e., the pipe / conduit / tray / duct does not fall and hit someone in the head due to inertial shaking).

Willy-nilly addition of lateral braces to commodities will reduce their flexibility, increase their fundamental frequency, impart higher thermal-induced stresses, impart higher stresses due to independent support displacement motions. The higher fundamental frequency will often lead to higher inertial stresses within the commodity (say from altering the frequency from 0.5 hertz to 5 hertz, one usually goes "up" on the spectral response in the response spectra). So, why add them for non-essential commodities, other than to add to project cost?

If the Owner truly wants the commodities to remain functional after the earthquake, then one of two rational choices are available: follow the stress rules of the ASME code (where R is 1) and make sure that the pipe (pipe joint, conduit joint, etc. remains within allowables); or use some simple / inexpensive rules (but also accept a somewhat higher chance of failure as not all high stress points will be quantified). Issues to be considered in performance-based seismic design of above ground piping, raceway, conduit and HVAC ducts are as follows:

- Pipes (and raceways, conduit, ducts) that cross expansion joints between adjacent structures should be provided with expansion fittings, multiple bends or other suitable provisions to ensure their capacity to sustain expected differential movements between independent structures (or any other permanent ground deformation). This can be relaxed if the stress / load in the pipe and pipe joints (or cable tray, conduit, duct) is shown to be satisfactory.

- Special care shall be taken to ensure that small branch lines off pipe headers do not by virtue of their attachment to structures or equipment, act as the brace for the pipe header unless demonstrated by calculation to have suitable capacity for this service.

- Pipes that contain very hazardous materials (e.g. chlorine gas) should be stress analyzed following the provisions of the ASME code to ensure that stress levels in the pipes and attached components are within allowables. Any steel pipe commodity may be designed for seismic loading using the stress criteria in the ASME code; and other types of pipe, cable tray, conduit and ducts may be designed using similar strength-of-materials procedures.

The Owner should not be forced to install lateral braces on commodities (pipes, conduits, cable trays, HVAC duct) for seismic loads for life safety purposes as long as vertical load carrying capability is maintained (applies to both new and existing construction). Lateral braces should be used when the combined commodity/support system is stress checked and for performance based design, shown that the supports are needed to maintain the functionality of the commodity. Lateral supports are often needed for thrust loads on water pipe systems. In most cases, yielding or damage to the supports is inconsequential to the Owner and can be readily repaired post-event.

Code Implications

A complete re-write of the sections of current codes dealing with seismic design of non-structural equipment and commodities is needed. The revised / rewritten code should have two sets of seismic rules for such items: first, for items that have only life safety implications; and second, for items that are required to remain in service after the earthquake. For most non-structural items, the relationship between these two goals *cannot* be simplified by increasing I from 1.0 to 1.25 or 1.5; instead, a different set of rules is required for components that are required to remain functional. The selection of R for commodities items *must* consider the type of pipe used, the type of joinery used (screwed or welded or bolted, etc.), and the performance based objective for the commodity (maintain pressure boundary, allow minor leaks, prevent cable tearing, etc.).

Until such time that the building codes (UBC, IBC, ASCE 7 et al) are revised, cognizant Owners can take the following approach:

- If only interested in life safety: follow current codes, but eliminate most of the lateral braces for commodities. This will save money and quite possibly increase functionality.
- If interested in reliable continued service: design commodities using the ASME code (such as B31.1); or use design-by-rule to eliminate the most common reasons for damage to commodities in past earthquakes. For commercial nuclear power plants, the ASME code approach is required, coupled with keeping all commodity supports elastic. For critical infrastructure (like a water treatment plant), the ASME approach for pipe stress is suitable, and some damage to pipe supports can be tolerated, as long as the total damage is rapidly repairable within the utility's post-earthquake performance goals. For commodities with high life safety risk (like chlorine gas pipes), the full adoption of ASME design rules (pipe and supports) is recommended. For most pipes and commodities, evaluation to show they can accommodate any likely imposed seismic anchor motions (inter-building movements, ground settlement, etc.), coupled with dead weight and water thrust restraint, and allowance for thermal expansion, will usually provide a good outcome of low initial capital cost and very good post-earthquake performance.

Operability Issues

If post-earthquake operability of equipment is critical, operational seismic qualification may be based on test or experience with similar equipment. There is no economic justification to applying the qualification requirements of IEEE 344 for equipment except at nuclear power plants or other extreme high hazard facilities. It is doubtful that imposing IEEE 344 would be cost effective for facilities such as hospitals, water treatment plants, etc.

Conclusions

Fragility models for "default use" with FEMA BCA are presented. The models are also suitable for loss estimation for large quantities of non-structural components. The fragility models should not be used for evaluation or design of specific pieces of equipment unless they are calibrated for site-specific application. Codes should be updated to match the performance based design implications implied by the fragility models.

References

Eidinger, J. M., Fragility of Non-structural Components for FEMA Benefit Cost Analysis, http://homepage.mac.com/eidinger/FileSharing15.html, May 27, 2009.

FEMA, Benefit Cost Analysis Toolkit Version 3.0, July, 2006. Includes Limited Data Module for Benefit-Cost Analysis of Non-Structural Seismic Hazard Mitigation Projects, http://www.fema.gov/government/grant/bca.shtm