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NONSTRUCTURAL VULNERABILITY FUNCTIONS FOR BUILDING CATEGORIES

by

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The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
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Nonstructural Vulnerability Functions for Building Categories
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Nonstructural building components account for the majority of building construction cost and as a result, their damage in earthquakes can dominate repair costs. The relationships between earthquake excitation and repair cost for nonstructural components are sometime depicted in seismic vulnerability functions. These relationships can be used at the level of individual buildings, as in ATC-58 (Applied Technology Council 2012), but there is also a need for such relationships at the level of building categories, for use in societal-level risk modeling. This work addresses the latter problem. There are several ways to address the problem: 1) by empirical means (relating aggregate nonstructural loss to ground motion through regression analysis); 2) by analytical means (relating structural response to component-level damage, which is then related to repair costs); and 3) by expert opinion. This work deals with analytical means. There is a growing library of component-level fragility functions for nonstructural components, and at least in the United States, an extensive database of costs for performing repairs. These enable the development of analytical relationships between structural response and nonstructural loss. Our intention is to produce and illustrate a method for developing broadly applicable analytical seismic vulnerability functions for non-structural components of buildings defined only by broad categories of material,

lateral force-resisting system, and height. The methodology is developed with collaboration and supervision of Professor Keith Porter at the University of Colorado Boulder and is intended for use as a guideline by the Global Earthquake Model.

A central challenge in such an effort is that the source data can be highly detailed. These detailed elements must be aggregated to systems and thence to all nonstructural components. So we (the present author with assistance and feedback form collaborators in the GEM project) have developed the methodology with a broad-brush approach, using cost manuals to identify the 4 or 5 systems that contribute the most cost to a typical building of the given category, and determining from a modest sample of buildings within the category of interest the detailed components that appear to be most common within those systems.

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CHAPTER I

INTRODUCTION

There is a rich literature of seismic vulnerability information, only exceeded by the vast need for more. Methods to derive new seismic vulnerability functions can be categorized into three types. In generally decreasing order of credibility they are empirical method, analytical method, and expert opinion. Particular implementations often include elements of two or more of these categories.

The empirical approach represents the best standard of seismic vulnerability. In this method, historical loss data are grouped by asset type (e.g., stone masonry buildings), data for a group are plotted on a graph with loss on the y-axis and estimated excitation on the x-axis, and a regression analysis is performed to fit a curve to the mean or median value, and quite often to the residual error. The second approach, analysis by engineering principles, provides insight that empirical methods do not, but can be costly and can lack the built-in validation of empirical methods. The third approach, expert opinion, is the most efficient of the three, requiring little analysis but offering little in the way of validation. The present research addresses the second approach, or rather a subset of it: vulnerability of non-structural building components.

Non-structural components constitute the majority of the construction cost of buildings, contributing around 60% (Whittaker and Soong, 2003). By non-structural components, one means any component in a building that does not significantly contribute to resisting lateral or vertical loads. Nonstructural components include: terminal and package units, plumbing fixtures, lighting and branch wiring, partitions, doors, window etc.

To estimate repair cost of damaged buildings in earthquakes on a component-by-component basis, one needs to calculate the repair cost of damaged non-structural components. (To estimate structural repair costs is a modest extension of the process described here, but the extension is not directly addressed here.) The repair cost is useful for different purposes such as determining the risk of insuring buildings. Furthermore, the cost is useful for determining performance of buildings in terms of probability of their repair cost in the PBEE-2 (Performance Based Earthquake Engineering, 2nd generation) methodology.

The most current method of calculating repair cost of earthquake-induced non-structural damage is the one introduced in ATC-58 (Applied Technology Council 2012). The current ATC-58 method is probabilistic and determines all the non-structural components in a building and measures all their quantities. Then the method uses the available unit repair cost database to calculate the total non-structural components repair cost for each seismic excitation. Despite the high accuracy of the method, the time and effort that it requires prevents a user from estimating the repair cost of large numbers and categories of buildings.

1.1 OBJECTIVES

In the current work, the intention is to produce broadly applicable analytical seismic vulnerability functions for non-structural components of buildings, including a number of state-of-the-art analytical functions using the PEER (Pacific Earthquake Engineering Research Center)/ATC-58 methodology.

There are so many non-structural components in a building that measuring them all is not feasible in terms of time and effort, especially, if one is dealing with a vast number of buildings in a city or a region. Hence, another main purpose of the proposed methodology is having an easy and fast, yet acceptably accurate methodology for estimating non-structural component repair cost.

The same concern is also correct for building categories. There are generally several different building categories in a city or region. Therefore, the technique of determining their non-structural component repair cost should be applicable to all different building types and categories, based on occupancy, height, structural material and lateral force resisting systems (LFRS). Therefore, the proposed methodology is designed to be applicable to different building categories or “models” as defined in the RSMeans Square Foot Cost (2009) construction cost manual.

Another concern in determining the repair cost of non-structural building components is taking into account the installation (such as type of anchorage) quality of the components in a building. The installation quality affects the performance of non-structural components in terms of their resistance against damage due to earthquake excitations. Therefore, the proposed methodology takes into account installation qualities of non-structural components in a building. In fact, the methodology categorizes the installation qualities into three types, poor, typical and superior, and determines repair cost based on these qualities.

The process of vulnerability assessment requires numerous assumptions and uses many approximations. As a result, there are uncertainties at every step in the analysis that need to be identified and quantified. Moreover, loss estimation requires integration of the (uncertain) ground motion as well as the (uncertain) vulnerability. The present study addresses only uncertainty in the vulnerability assessment, including uncertainty in which components are used in the various buildings that comprise the asset class, what structural response they experience at various levels of ground motion, the damage they experience, and the cost to repair that damage. Thus, it is important to develop methods for propagating and combining the uncertainties from each step of the analysis.

The result from applying the methodology should be applicable to earthquake risk assessment of buildings at the level of the city or region.

1.2 ORGANIZATION OF THE THESIS

In the following chapters, first, some literature on earthquake reconnaissance reports, as well as the most relevant literature on the subject of the current work is reviewed in Chapter 2. Next, the methodology is described in a step by step procedure in Chapter 3. In Chapter 4, an example of applying the methodology to an index building will be offered for more clarification. In Chapter 5, the results and findings about applying the methodology, sensitivity tests and uncertainty test will be discussed. Chapter 6 presents conclusions and recommendations.

CHAPTER II

REVIEW OF THE LITERATURE

2.1 RECONNAISSANCE REPORTS

In this section, a few earthquake reconnaissance reports from several earthquakes around the world are reviewed to identify the most damageable nonstructural components. It is also focused on nonstructural components in terms of their behavior and the most dominant types of damage due to earthquakes. The reconnaissance report summaries are all from the Preliminary Reconnaissance Reports provided by the Earthquake Engineering Research Institute after each earthquake. They include reconnaissance reports from many major earthquakes of the last 50 years from all around the world. Not every reconnaissance report contains useful details about the performance of nonstructural components, and there is some repetition from event to event. The following list appears to provide a reasonable overview of common damage to nonstructural components.

Niigata earthquake, M 7.5 (16 Jun 1964)

1) Excessive drifts in some steel-framed buildings caused damages to infill walls and glazing in industrial building.
2) Excessive drift in some RC buildings caused major cracks in infill walls.
3) Some houses only suffered broken glass

4) Uneven sinking caused damages to floor finishings and some infill walls in some buildings.
5) Separation of cement plastering from walls was seen. Also, separation of mud finishes was seen.
6) In some steel truss roof buildings, "half of the lighting cases with fluorescent bulbs fixed directly to roof trusses with tapping screws fell down at the seismic shock."
7) In some steel truss roof buildings, cladding slipped off the wall
8) In a factory, piping was damaged due to depression of concrete flooring.

San Fernando Earthquake: M 6.6 (9 Feb 1971)

1) Machinery was toppled where beams fell from supporting pilasters in an industrial complex.
2) Unanchored storage racks collapsed.
3) Telephone equipment damage in a basement of a medical treatment building was seen.
4) Fallen ceiling tile was seen on the first story of medical treatment building.
5) Most of the failure comes from unanchored and poorly anchored equipment.
6) Broken piping was seen at the central heating and air conditioning room of the building. Also, fallen unanchored batteries required for activating

standby power operation. Emergency generator went off its mountings and was inoperative.

Miyagi-Ken-Oki, Japan, M 7.7 (June 12, 1978)

1) In general, architectural damage was minimal. Highrise buildings performed well.
2) Several damages were observed to infill walls and veneer.
3) Suspended ceilings and interior ceiling frames were damaged in many cases
4) Glass with hard putty sealant tended to break, compared with glass with a floating seal or silicone sealant.
5) Non-structural damage seemed to relate to structural flexibility, with more damage in more-flexible buildings.

Thessaloniki, Greece, M 6.6 (June 20, 1978)

1) Falling plaster in traditional buildings was seen.
2) Hollow-tile facade collapsed

The Mexico City earthquake, M 8.1 (19 Sept 1985)

1) Some damage due to in plane and out of plane stresses happened to rigid infill walls. The damage mostly happened in 5 to 15 buildings.
2) Glass curtain walling fared much better than the blockwork, and in general only serious breakage appears to have occurred in buildings with major structural damage.
3) Some buildings with no structural damage suffered extensive internal cracking of plaster, damage to false ceilings, etc.
4) Roof-mounted RC water tanks, which were supported on 4 stub columns, fell from an eight story block.

Northridge, USA, M 6.7 (17 Jan, 1994):

1) Well installed and well anchored non-structural components had significantly less damage compared to unanchored or loose components.
2) Non-structural damage even without structural damage caused temporary closure, evacuation or patient transfer in several hospitals in the area.
3) In some hospitals, water leakage took a great deal of time to be locate and repaired.
4) The main non-structural damage was single story large-pane store front damage compared to other non-structural damage. The reason was extensive drift of the first stories.

5) Code-compliant suspended ceilings installments did not undergo general damage but did experience some local damage.
6) For some stores, widespread damage to non-structural components (e.g., suspended ceilings, lighting, racks and shelves) occurred, even though the exterior of the building was fine. Diagonal tension wires supporting suspended ceilings seemed effective in reducing damage to suspended ceilings.
7) Some damage was observed due to water leakage from sprinklers.
8) Widespread damage was observed to infill walls and partitions, as well as damage to soffits and veneer.

Hyogo-Ken Nanbu earthquake (Kobe), M 7.2 (17 Jan 1995)

1) Low-rise buildings with soft-story conditions at the ground floor underwent excessive drift, which caused damage to infill walls and glazing.
2) Windows and glazing damage was seen in several midrise buildings in downtown Kobe that had no structural damage

El Quindio, Colombia M 6.2 (Jan 25, 1999)

1) Unreinforced masonry infill walls, masonry veneer and partitions experienced severe and widespread damage. No separation was observed between walls and surrounding frames.
2) It's not common to use suspended ceiling in Colombia but severe damage was observed in buildings that did have suspended ceilings.
3) Water piping was embedded in slabs and no damage was observed. Overturned cabinets and shelves were seen.

Chi-Chi earthquake, M 6.8 (21 Sept 1999)

1) Well anchored sprinkler piping and lighting were not damaged.
2) Structural drift caused cracks on wall finishes although the structure wasn't damaged.
3) Failure and collapse of some construction equipment such as cranes caused damage to structural and non-structural components nearby.

The Boumerdes, Algeria, M 6.8 (May 21, 2003)

1) Typical building construction for apartments and single family dwellings was reinforced concrete frame with hollow unreinforced brick infill.
2) Cracking in masonry infill was widespread.
3) Falling of masonry infill walls was observed.

4) No failure in infill walls in steel structures was observed

Port-au-Prince, Haiti, M 7.0 (12 Jan, 2010):

1) The main damage to non-structural components was from unanchored or poorly installed components, while well installed components fared better.
2) Damage due to non-structural components due to debris was the second main reason of all non-structural damage.

According to the reconnaissance reports mentioned above, most of the damage in non-structural components occurred due to lack of anchorage. Those components that were well anchored tended to resist damage. Therefore, anchorage is a key element in terms of the performance and safety of non-structural components in buildings.

In general, in most of the reconnaissance reports, little information on non-structural performance is available compared to information on structural performance and damage.

In addition, as it was seen in the reports, significant damage happened to external windows and storefront glass walls due to excessive drift. Excessive drift often happened at ground level because of soft-story effects. Also, partitions were usually damaged due to excessive inter-story drifts throughout buildings. However, suspended ceilings were damaged mostly because of lack of diagonal bracings that connect the ceilings to building structure. Most of the damaged ceilings were anchored for vertical loads, but they were not anchored diagonally to resist against horizontal accelerations.

2.2 NONSTRUCTURAL VULNERABILITY MODELING

In this section, literature regarding modeling of the seismic performance of non-structural components is reviewed and briefly described.

There are several studies that produced empirical fragility function for nonstructural components: Porter (2007), Porter et al. (2007, 2010) Porter and Cobeen (2009), Johnson et al. (1999), Kao, et al. (1999), ATC-38 (2000), and various other works in prepared for use in ATC-58 (wallboard partitions, glazing, stone cladding, etc.). These nonstructural fragility functions can be employed in empirical vulnerability functions (especially ATC-38) and more likely in deriving analytical vulnerability functions, perhaps by methods similar to those offered by Porter and Cobeen (2009).

Czarnecki (1973) introduced what seems to be the first analytical method for estimating seismic vulnerability. His work is component based. It begins with a structural analysis to estimate member forces and deformations in response to a particular level of shaking. It then offers a kind of combined damage and loss analysis. It employs a method of finding damage to building components by comparing absorbed energy in the building components to the maximum energy absorption capacity of the components. The method is applied to several tall buildings damaged by the 1971 San Fernando earthquake. The result shows that the method predicts a general trend of damage but might come with considerable error in any specific case.

Kustu et al. (1982) built upon the work of Czarnecki (1973) and provided component damage function from available laboratory tests to calculate total damage to tall buildings. They used structural response, mostly story drifts, as demand parameters for the damage curves. They distinguish damage from loss, and employ the test data for the damage analysis.

Kircher et al. (1997) offer what appears to be the first analytical method applied to virtually every building type in the US. The method applies pushover structural analysis using a single-degree-of-freedom (SDOF) nonlinear oscillator to represent a building, or rather each building type. They characterize the building as comprising three aggregate components: a drift-sensitive structural component that is supposed to represent all of the beams, columns, shearwalls, etc. in the building, a drift-sensitive nonstructural component (representing all partitions, glazing, etc.), and an acceleration-sensitive nonstructural component (floor-mounted and slab-suspended equipment). The methodology is intended for catastrophe risk modeling at the societal level. The methodology is based on quantitative seismic excitations.

Algermissen and Steinbrugge (1984) have examined several methods involved in seismic risk assessment. The methods consist of three main categories of hazard estimation, development of building inventories, and loss associated with certain level of hazard. The purpose of their work is to evaluate the accuracy of seismic risk assessment considering uncertainties in each category.

Wesson et al. (2004) provided data for a large population of residential, mostly woodframe, buildings shaken by the 1994 Northridge earthquake and derived an empirical, parametric, probabilistic model of repair cost (as a fraction of replacement cost new) as a function of shaking. This work appears to be one of the most comprehensive empirical vulnerability models ever created. The comparison between the estimated loss curves and actual data from after earthquake loss calculation shows a satisfactory agreement.

Porter (2007) offers an example of how to develop an empirical fragility function for building components. He derives fragility functions for hydraulic elevators based on a post-earthquake survey of 91 elevators shaken in the Loma Prieta and Northridge earthquakes. The input demand parameter is PGA, estimated by spatial interpolation between the two nearest accelerometers. To verify the quality and acceptability of the fragility functions, the author describes (1) whether the value of the logarithmic standard deviation of the fragility function lies within the (typically observed) range of 0.3 to 0.6; (2) how well established is the 10th percentile failure EDP (i.e., the value of EDP at which the fragility function indicates 10% failure probability); (3) how many specimens were employed to establish the fragility function; and (4) how robust the fragility function is to the analysis method.

Porter et al. (2007) offer six standard methods for deriving fragility functions that express the probability of damage to building components versus a measure of seismic excitation, such as the structural response to which the components are subjected (typically deformation, acceleration, and in the case of some structural components, member forces). The authors limit their discussion to fragility functions that take the form of cumulative lognormal distribution functions. Which method is used depends on the available excitation and damage data. They are: A. actual failure EDP (all specimens failed at known levels of excitation), B. Bounding EDP (some specimens failed, some did not, and the maximum excitation to which each specimen was subjected in known, but not the level of excitation at which they failed), C. Capable EDP (no specimens failed, and the maximum level of excitation to which each specimen was subjected is known), D. Derived fragility (by first principles), E. expert opinion, and U. updating (an existing fragility function is revised in light of new evidence using Bayesian updating). Finally, to check the acceptance of the derived fragility function, the authors introduce a goodness of fit checking procedure. In the goodness of fit test, the uncertainty value calculated by the suggested function is compared with the minimum critical acceptable value.

Porter et al. (2010) apply the Porter et al. (2007) methodologies for deriving fragility functions for mechanical, electrical and plumbing equipment, mostly using historic earthquake experience data in the eSQUG database (EPRI 2007). An important point in the article that can be usable in the current research project for deriving fragility functions for non-structural components is "installation techniques" and their effects of damage probability besides height distribution and sensitivity to acceleration and drift of equipment locations within buildings.

Porter and Cobeen (2009) describe a seismic risk study of four "index buildings," which are used as proxies for 2800 large woodframe buildings in San Francisco. The objective is to derive their level of safety in four earthquake scenarios. Damage and economic loss is also calculated under as-is and three retrofit options for each index building. Performance is calculated using pushover analysis and calculated fragility functions as is done in HAZUS-MH. Unlike HAZUS-MH however, new fragility functions are derived for the major structural and nonstructural components of each index building along the lines suggested by Porter et al. (2007).

Jaiswal and Wald (2010) derive empirical fatality-rate functions considering country or regional characteristics that can affect the outcomes of the fatality probability functions (population killed divided by total population exposed). The offered methodology is based on considering two cumulative lognormal distribution functions to achieve the best fit for both more numerous low-fatality events and high fatality earthquakes. The effective parameters that contribute in deriving regional based fatality functions are based on geography, climate, and building inventory of each region under consideration. Those effects are available from Human Development Index (HDI) and climate classification. By gathering the regional fatality ratio at earthquake intensities, one can derive fatality-based alerts that work everywhere in the world and notify authorities about possible range of fatalities after an earthquake event. The concept of applying regional data such as building inventory can be applicable in using this methodology for regional level risk assessment.

The idea of regionalization of the fatality distribution functions is applicable for fragility functions to gain better estimates for a specific region under consideration. Also, using two cumulative lognormal distribution functions to fit the whole range of excitations is applicable for the current research project.

As mentioned earlier, one of the main issues for determining non-structural fragility functions is to determine the probability of usage of various detailed types of non-structural components. One way to do that is to use experts' opinions. To utilize experts' opinion, one should define a clear and organized procedure so that everybody can follow it. Below, a brief introduction to the Delphi process is presented.

2.3 DELPHI PROCESS

The Delphi process is a systematic method of collecting and processing expert opinions about an uncertain event or quantity (Dalkey 1969). To achieve higher reliability of the result, the subject of the event should be within the expertise of the experts. In general, the Delphi process starts with creating and distributing to experts a questionnaire with clear questions about the subject, asking them to make their best judgment about the questions and, write down their answers. If the expert judgment indicates significant disagreement between experts, a second round of questioning is undertaken. In the second round, the coordinating team collects the questionnaires from all experts and resends the answers back to the experts asking them to make a new judgment based on the new information from the other experts' opinions. Also, the experts are asked to explain their new judgment. The same process should continue until an acceptable convergence of the results is achieved. Cooke (1991) suggests calculating the mean and standard deviation of the results in each round and informing those experts with estimation below the 25th or above the 75th percentiles about their answers location. This information might help those experts to modify their estimate in later rounds.

For better performance and accuracy improvement of the Delphi process, some scholars have suggested several revisions (Cooke 1991, Dalkey et al. 1970, Martino 1970). First of all, the coordinating team needs to keep the experts names confidential from other experts during the whole process, or even after the process. The confidential procedure removes the pressure on experts, for keeping their reputation, to stick on their judgment for the next rounds. For further improvement, a self-rating technique can be used to increase the accuracy of the result. In the self-rating technique, the experts are asked to rate their confidence on each of their answers. By using these rating data, the coordinating team can exclude experts whose confidence is low or weight each expert's response using confidence level as a weighting factor. This tends to lead to more reliable results with higher accuracy.

Another expert weighting method is suggested by De Groot (1974). In this weighting method, each expert weighs all the other experts based on their answers in each round. All weight data essentially will be used to rate the opinion of each expert. Another method of increasing reliability and accuracy of an expert opinion procedure is applying pre-known questions. In this technique, the coordinating team asks questions for which answers are already known by the coordinating team, but are not in hand for the experts. Therefore, the coordinating team can weight each expert regarding his/her knowledge on the subject under evaluation.

Finally, two points are notable. First: using a higher number of experts will lead to higher accuracy and reliability of the results (Dalkey et al. 1970). Second, there is a relationship between remoteness of event and uncertainty of forecasts. In fact, the more remote the event is the higher uncertainty in forecasting by experts (Martino 1970).

A good recent example of applying expert opinion to derive building vulnerability functions by using Delphi process is ATC-13. I used the ATC-13 functions to compare the results of the illustration example in Chapter 4.

2.4 LITERATURE ON THE SIMPLIFIED NONLINEAR STRUCTURAL DYNAMIC METHOD

The foregoing section addresses challenges to defining the asset at risk. Once the asset is defined, one must perform structural analyses to estimate the structural response to which nonstructural components are subjected. Let's consider available literature on structural analysis, with an emphasis on simple methods.

In "Nonlinear Analysis Method for Performance Based Seismic Design," Fajfar (2000) offers a simplified method for nonlinear seismic analysis of structures. The method applies pushover nonlinear analysis methods to determine lateral force resistance capacity of structures and, a demand spectrum which is based on response spectrum analysis. In Fajfar's method, the demand diagram is determined by converting pseudo-acceleration, as a function of period of structure, to elastic acceleration, as a function of spectral displacement, for each of many damping values. The capacity curve of the structure is determined by pushover. To run the pushover analysis, one needs to assume a force distribution through the height of the structure and multiply it by its mass matrix and by the increasing value of lateral force.

To find the displacement of each story, the demand curve and the capacity curve are superimposed and the intersection of the two graphs shows the modal displacement. The procedure starts with finding an equivalent single-degree of freedom system for the multiple-degree of freedom system. After finding the displacement of the top story of the equivalent system, one needs to transfer it back to the displacement of the top story of the multiple-degree of freedom system. Also, according to the author, the method cannot model higher-modes effects. The method mostly works for medium to high range periods.

The N2 method has been selected as a simplified structural analysis method for the GEM guidelines. In this work, as a part of the GEM project, the N2 method is introduced and is described as one option for performing structural analysis.

Chopra and Goel (2001) introduce two procedures for nonlinear seismic analysis of structures. The first method is response history analysis in which a multi-degree-of-freedom system (MDF) is decoupled into single degree of freedom systems (SDF). For each SDF, the equation of motion is solved with considering changes in stiffness value with respect to displacement and velocity. After finding the displacements of each story for each mode, the modes are added together using the method of square root of summation of squares. The solution of the equation of motion for each mode can be determined by either structural dynamic or pseudo dynamic methods. The second method is pushover analysis. In the pushover analysis, similar to the previous method, a MDF system should be decoupled into SDF systems for each mode. After decoupling, the structural response for each mode should be determined by applying increasing force with an assumed distribution on the structure and find the response by considering change of dynamic properties of the structures as the load increases. Finally, a graph which shows the applied force versus displacement can be determined. The accuracy of the two methods is shown to be sufficient for practical engineering projects.

With regard to complexity and accuracy of the methods above, pushover analysis seems the most reasonable method to apply for determining vulnerability of nonstructural components, balancing the desire to reflect nonlinear behavior with a need for simplicity when applied to a large numbers of buildings.

2.5 BASIC CONCEPT OF FRAGILITY FUNCTIONS

Because fragility functions are central to the present research, a brief recap of one of the most common forms of fragility functions is offered here. Fragility functions of nonstructural components are commonly modeled using a lognormal cumulative distribution function. ATC-58 (Applied Technology Council 2012) does so, but the practice goes back several decades. The fragility function shows the relationship between input excitation (such as drift ratio) and the probability of a specimen reaching or exceeding a certain damage state. A lognormal fragility function is fully defined by a median and a logarithmic standard deviation. Some components can have more than one damage state and, for each damage state, there is a distinct fragility function.

Below is the most common used equation for fragility function with the median θ and the logarithmic standard deviation β for component i and damage state d for seismic excitation s.

$$P[D_i \geq d] = \Phi\left(\frac{\ln\left(\frac{s}{\theta_{id}}\right)}{\beta_{id}}\right) \qquad (1)$$

Below is a sample fragility function for a particular kind of gypsum wallboard partition on metal studs, a component with two damage states.

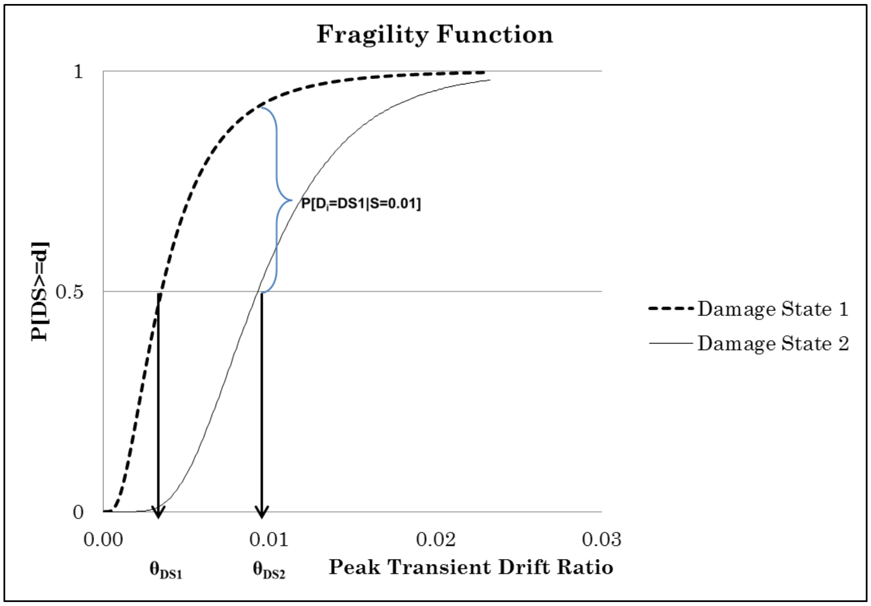


Figure 1: Fragility functions for gypsum wallboard partitions with two damage states. The probability in being in damage state 1 conditioned on 1% story drift is shown.

The median value for each damage state, θ_{DS1} and θ_{DS2}, and the probability of being in damage state 1, $P[D_i = DS1|S = 0.01]$ for story drift S=0.01 as an excitation, are illustrated in Figure 1.

CHAPTER III

RESEARCH METHODOLOGY

This chapter presents a methodology developed for the Global Earthquake Model for deriving vulnerability functions for non-structural components of building categories. By “building category”, i.e. a group of buildings with common features, especially material, lateral force-resisting system, occupancy and height. The goals of the methodology are: first basic skillset (any structural engineer with a master’s degree should be able to use the methodology), fast (hours to days, not days to weeks, so that several buildings in a class can be practically assessed), geography (global), applies to asset class as oppose to single building, versatile (as simple or as sophisticated as a structural engineer desires).

To be clear, the present study focuses on deriving whole-building nonstructural vulnerability functions for a building category by analytical means, in particular, by a simplified version of PBEE-2. An important challenge is how to define the building category, that is, to describe and quantify the nonstructural components in the building. For the sake of simplicity and clarity, the methodology is divided in three main steps, as follows.

3.1 STEP 1: SELECT INDEX BUILDINGS AND IDENTIFY TOP NON-STRUCTURAL COMPONENTS

The method relies on the concept of an index building, that is, a real or hypothetical building designed in some detail and intended to be somehow representative of a broader class. For convenience, index buildings can be defined by reference. For example, the analyst can pick the most-similar building model in the RSMeans Square Foot Cost (2009) manual or any other construction cost reference that considers occupancy, structural material and height, such as ONDAC in Chile (http://www.ondac.com/principal.htm) or the BCIS Comprehensive Building Price Book in the United Kingdom (BCIS 2012a).

Next, one determines the story-by-story quantity and construction cost of nonstructural components that have the largest contribution to non-structural construction cost. As it will be seen through sensitivity tests results, it is sufficient to quantify the 5 or so nonstructural component categories that contribute most to the construction cost (new) of the index building. These are referred to as the top nonstructural component categories. Components are categorized here by the NISTIR 6389 (NIST, 1999) extension to the US National Institute of Standards and Technology UNIFORMAT II system (NIST, 1999). By “story-by-story quantity”, i.e. the quantity of each component on each story, measured in units most commonly used for construction cost estimation, such as linear feet of partition, square feet of suspended ceiling, and number of elevators.

3.2 STEP 2: DERIVE COMPONENT VULNERABILITY FUNCTIONS

Next, one creates aggregated vulnerability functions for each top non-structural component to relate story-level seismic excitation to repair cost per unit of the component. By "aggregated vulnerability function", i.e. that the vulnerability function reflects uncertainty in the details of each component. By "details", i.e., for any given component category such as gypsum wallboard partition, there are details of the configuration, installation condition, size, damage states or other characteristics that matter to seismic fragility, so there are subcategories of the component each with their own sets of fragility functions. These details are straightforward to represent when analyzing a particular building, but too detailed for a building category, so they are aggregated.

One can think of the aggregated nonstructural components discussed here as grouped by the UNIFORMAT II or slightly more-detailed NISTIR 6389 (NIST 1999) labeling system, which label each building component with a 5-character hierarchical code of the form X0000. At its most-detailed, this system differentiates building components between, say, C1011 = fixed partitions, C1012 = demountable partitions. But within one such category the seismic vulnerability can vary greatly, e.g., between gypsum wallboard partitions with full-height sheathing and fixed top plates, and gypsum wallboard partitions with partial-height sheathing. The ATC-58 project (ATC, 2012) and the present research use fragility functions at this latter level of detail, referring to them as detailed vulnerability functions. These are then aggregated by applying the theorem of total probability, i.e., considering the probability that each detailed type is used, given that the aggregated type is used.

The present work relies on existing databases of detailed nonstructural components' fragility functions, especially that of the ATC-58 project, though the analyst is free to derive new detailed component fragility functions or take them from other sources.

Below is the method of aggregating vulnerability functions for different damage states and different sizes or capacities of a non-structural component h;

$$E[C \mid S = s, H = h] = \sum_{i=1}^{N_i} \sum_{d=1}^{N_d} P[D_i = \mathrm{d} \mid S = s] \cdot E[C \mid D_i = d] \cdot W_h(i) \tag{2}$$

E[A | B]: expected value of the uncertain variable A given knowledge B

C: repair cost, here of the aggregated component category h, measured in units of currency

S: seismic excitation imposed on aggregated component category h (also referred to as the demand parameter); can be measured in terms of member force, member deformation, acceleration, or other measure. Most commonly S is measured in terms of peak transient drift ratio or peak floor acceleration, although residual drift, peak floor velocity, and sometimes other demand parameters are used.

H: a variable that indexes aggregated component categories

h: a particular value of H, i.e., an index to a particular aggregated component category

i: an index to a detailed component category within the broad component category h

N_i: number of possible detailed component categories i within broad component category h

D_i: uncertain damage state of detailed component category i

d: a particular value of D

N_d: number of possible damage states that detailed component category i can experience, in addition to the undamaged state

$W_h(i)$: Fraction of components in aggregated category h that are of detailed type i, Default is $\frac{1}{N_i}$ and must sum over N_i to 1.0.

$E[C\ |D_i = d]$: mean repair cost for a unit of detailed component category i that is in damage state d.

$$P[D_i = d\ |S = s] = \Phi\left(\frac{\ln\left(\frac{s}{\theta_{id}}\right)}{\beta_{id}}\right) - \Phi\left(\frac{\ln\left(\frac{s}{\theta_{id+1}}\right)}{\beta_{id+1}}\right) \qquad for\ 0 < d < N_d \qquad (3)$$

$$P[D_i = d\ |S = s] = \Phi\left(\frac{\ln\left(\frac{s}{\theta_{id}}\right)}{\beta_{id}}\right) \qquad for\ d = N_d \qquad (4)$$

The required parameters above are

θ_{id}: median capacity of a component of detailed type i to resist its damage state d. Let us refer to this as the median of the (i,d) capacity.

β_{id}: logarithmic standard deviation of the (i,d) capacity.

Φ: standard normal cumulative distribution function.

The parameters θ and ß can be taken from existing libraries of fragility functions, especially that of ATC-58 (2012) or Johnson et al. (1999) Appendix C. Or they can be derived from available sources using the procedures specified in Porter et al. (2007). The mean consequence functions $E[C|D_i = d]$ can likewise be taken from an existing library such as ATC-58 (2012), from locally appropriate repair-cost guidelines such as Xactimate (Xactware, 2012) or BCIS (2012b), or from available local construction-contracting expertise. In PACT database, which is the same database used by ATC-58, includes information for loss in terms of dollar/death/downtime such as: component name, median demand for damage states, total dispersion for damage states, data quality and relevance, repair description for damage states.

The last term of the above equation, $W_h(i)$ is the weighting item in which the probability of usage of the nonstructural component of the database is determined. One can imagine four methods to determine $W_h(i)$, as follows.

3.2.1 CALCULATION OF THE WEIGHTING ITEM, $W_h(i)$;

The weighting item, $W_h(i)$, can be determined using one or more of the following methods;

a) Primary-Guess Procedure:

The least expensive but also least controlled approach is for an analyst to guess the values of $W_h(i)$. The guesses should be documented with an explanation that includes: the analyst's construction or design experience, years in practice, consideration of the construction type, regional economy and climate (if applicable), and if possible, observations from actual buildings in the building category of interest.

b) Information From Local Construction Material Store

In each area or region, one reasonable source for determining the relative usage of specific nonstructural component sizes or capacities is local construction material stores. Weights $W_h(i)$ are taken from the relative amount or number of each size or capacity sold recently. This information might be available in the construction-materials department at the local store. By dividing the number or amount of the specific item size or capacity they have sold within a year by the total number or amount of the same nonstructural type but different sizes or capacities, one can calculate the probability of use of that specific item.

c) Expert Panel

One can assemble an expert panel comprising a few experts from the relevant fields of the specific nonstructural component under consideration. The expert panel could consist of a designer engineer who is familiar with the specific nonstructural component category, an architect, a local building official, and a construction contractor. The panel members should get together in a same place, be offered a description of the nonstructural component under consideration, and asked to reach a consensus on a reasonable mix of detailed component types, i.e., reasonable quantities of $W_h(i)$. The concept of nonstructural probability of usage and the question they need to answer should be clear to them at the beginning so they understand the reason for the question. To perform a more organized expert opinion procedure, one can follow the Delphi method (Cooke 1991).

d) Construction Drawings

A fourth approach to determine the probability of usage for non-structural components is to refer to architectural and MEP (mechanical, electrical and plumbing) design drawings for existing sample buildings in the region under consideration. The drawings can help one calculate the number of different sizes or capacities for each type of component used in the sample buildings as well as the total number of the components type used. By dividing the number of each size by the total number of component of all sizes and capacities, one can determine the probability of usage of that size or capacity.

3.3 STEP 3: DERIVING STORY-LEVEL NONSTRUCTURAL COMPONENT VULNERABILITY FUNCTIONS

To determine the average vulnerability of nonstructural components of an index building, one next aggregates vulnerability of non-structural components within each story of the building. For present purposes, and following the examples of HAZUS-MH (NIBS and FEMA, 2007) and ATC-58 (ATC, 2012), two demand parameters are employed: story drift and floor acceleration. Drift-sensitive components are generally those that are fixed to the floors below and above, such as partitions or exterior cladding. Acceleration-sensitive components are those that are fixed either below or above, or rest on the floor, such as switchgear. One separately sums vulnerability of drift-sensitive and acceleration-sensitive components. Below is the method of adding repair cost of components categories for both drift sensitive and floor acceleration sensitive non-structural components. For components sensitive to drift:

$$\mathrm{E}[C_{PTD,n} \mid S_{PTD,n} = s, M = m] = \frac{\sum_{h=1}^{N_{NH,PTD}} E[C \mid S_{PTD,n}=s, H=h] \cdot Q(h \mid M=m)}{F(m)} \tag{5}$$

Where:

$C_{PTD,n}$: (uncertain) repair cost of all drift-sensitive components on story n

M: a variable that indexes building models

m: a particular value of M, i.e., a particular index building

$S_{PTD,n}$: (uncertain) peak transit drift ratio of the floor of story n

$N_{NH,PTD}$: Number of top components that are sensitive to drift

$Q(h\mid M=m)$: quantity of component of type $H=h$ in a single story of a building of model m

$F(m)$: fraction of total non-structural construction cost that is contributed by the top components considered here, for the index building m

For components sensitive to peak floor acceleration;

$$E[C_{PFA,n}\mid S_{PFA,n}=s, M=m]=\frac{\sum_{h=1}^{N_{H,PFA}} E[C\mid S_{PFA,n}=s, H=h]\cdot Q(h\mid M=m)}{F(m)} \tag{6}$$

$C_{FPA,n}$: uncertain repair cost for all acceleration-sensitive components attached to the floor of story n

$S_{PFA,n}$: (uncertain) peak floor acceleration of the floor of story n

3.4 STEP 4: BUILDING-LEVEL NON-STRUCTURAL COMPONENTS VULNERABILITY FUNCTION

Finally, the repair costs of drift-sensitive and acceleration-sensitive components are added for the whole building, to find the total nonstructural repair cost as follows:

$$E[C\mid M=m, S=s]=\sum_{n=1}^{N_s+1} E\left[C_{PTD,n}\mid M=m, S_{PTD,n}=S_m^n(X)\right]+E\left[C_{PFA,n}\mid M=m, S_{PFA,n}=S_m^{Ns+n}(X)\right] \tag{7}$$

X: Uncertain shaking intensity, e.g., S_a(1.0 sec, 5%); the most-common being: $X \in \{PGA_{gm}, S_a(0.3\text{ sec}, 5\%), S_a(1.0\text{ sec}, 5\%), PGV_{gm}, MMI, EMS\text{-}98\}$

x: Particular value of X

$S_m^j(X)$: component j of the structural response for a building of model m, given X

N_s: Number of stories

3.5 STRUCTURAL ANALYSIS AND STRUCTURAL RESPONSE VECTOR, $S_M(X)$

Equation (7) needs to have a structural response vector $S_m(X)$ to calculate building level vulnerability. Here, the vector only contains peak transient drift ratio for each story and peak floor accelerations for each floor and the roof. It has $2N_s+1$ rows, in which the first N_s are peak transient drift ratios and the remaining N_S+1 are peak absolute floor accelerations. (For convenience, the drift calculated in one direction is assumed to apply to the other.) The structural response vector has the following format;

$$S_m(X)= [S_{PTD,1}(X), S_{PTD,2}(X),\ldots, S_{PTD,n}(X), S_{PFA,1}(X), S_{PFA,1}(X),\ldots, S_{PFA,n+1}(X)]^T \quad (7)$$

Where;

$S_{PTD,i}(X)$: Expected value of peak transit drift, story i, when building of model m is subjected to intensity X shaking

$S_{PFA,i}(X)$: Expected value of peak floor acceleration, floor i, when building of model m is subjected to intensity X shaking

Where

$$S_{PTD,i}(X) = \Gamma \times S_a(T, \%5) \times \frac{T^2}{4\pi^2}\left(\frac{\varphi_m(i+1) - \varphi_m(i)}{h_{i+1} - h_i}\right) \tag{8}$$

$$S_{PFA,i}(X) = PGA + \varphi_m(i)(\Gamma \times S_a(T, \%5) - PGA) \tag{9}$$

Let

T = fundamental period of vibration, sec. From structural analysis, local guidelines, or use defaults from ASCE 7-10:

= $0.0724Z^{0.8}$ steel moment-resisting frame

= $0.0466Z^{0.9}$ concrete moment-resisting frame

= $0.0731Z^{0.75}$ steel eccentrically braced frame or steel buckling-restrained braced frame

= $0.0488Z^{0.75}$ all others

Z = building height, meters

x = intensity measure type. Either use the same as for the structural vulnerability, or (for ease of comparison with other vulnerability functions), it can be taken as follows:

= Sa(0.3 sec, 5%) for index buildings with $T < 0.5$ sec. Here, spectral acceleration response is the geometric mean of two orthogonal directions.

= Sa(1.0 sec, 5%) for index buildings with $T \geq 0.5$ sec

Evaluate x at the following intensity measure levels:

x = 0.01, 0.02, ... 3.0g for index buildings whose structural analyses can be done cheaply, or

= $10^{-1.50}$, $10^{-1.25}$, $10^{-1.0}$, ... $10^{0.5}$ otherwise. These are 9 logarithmic increments, comparable with 8 suggested by ATC-58.

Sa(T,5%) = 5% damped elastic spectral acceleration response at T, geomean. Evaluate it at each value of x, either using a local conventional relationship or by default using.

Sa(T,5%) = Sa(0.3 sec, 5%) for $T < 0.5$ sec

= Sa(1.0 sec, 5%)/T for $T \geq 0.5$ sec

PGA = peak ground acceleration in units of g

≈ Sa(1 sec, 5%) for $T \geq 0.5$ sec

≈ 0.4 ·Sa(0.3 sec, 5%) for $T < 0.5$ sec

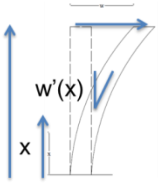
$\Gamma = \frac{\sum m_i \varphi_i}{\sum m_i {\varphi_i}^2}$ = roof acceleration as a factor of modal acceleration ≈ 1.3

φ_i= normalized displacement shape of the story i

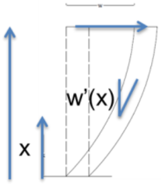
Therefore, by finding the roof displacement and acceleration, one can determine lateral displacement of all stories and floor acceleration of the building or $S_m(X)$vector. Ideally, the vector is the expected value of response produced by nonlinear dynamic structural analyses and varies nonlinearly with X. More simply, it might be the result of a nonlinear pseudostatic (pushover) structural analysis and vary nonlinearly with X. Or most simply, it could represent one of a few standard shapes and vary linearly with X. We do not discuss the structural analysis procedures that might be used in nonlinear dynamic or pseudostatic structural analyses.

Absent thorough nonlinear structural analysis, and motivated by the need to produce vulnerability functions for a class with a minimum of structural analysis effort, one could idealize the building's deflected shape as one of three cases: (1) for shearwall buildings, the deflected shape of a prismatic, elastic cantilever beam with effectively infinite shear modulus and finite Young's modulus and moment of inertia, subjected to a distributed horizontal load that increases linearly with height per ASCE 7 (2010) Sec 13.3. (2) For frame buildings, the deflected shape of a prismatic, elastic cantilever beam with constant shear modulus and cross-sectional area, subjected to the triangular ASCE 7 (2010) loading profile. (3) For dual systems or other intermediate cases, the deflected shape is taken as triangular, i.e., with constant peak transient drift ratio. The deflected mode shape in these 3 cases can be shown to be as follows, where w(x) denotes relative displacement at elevation *x*, in a building of height *h*:

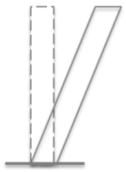
Shearwall: $$\varphi_m(i)=\frac{w(x)}{w(h)}\approx\frac{x^2}{h^5}\frac{\left(70h^3-40h^2x+5hx^2+2x^3\right)}{37} \qquad (10)$$



Frame: $$\varphi_m(i)=\frac{w(x)}{w(h)}\approx\frac{x}{h^3}\cdot\frac{12h^2-3hx-2x^2}{7} \qquad (11)$$



Dual system: $$\varphi_m(i)=\frac{w(x)}{w(h)}\approx\frac{x}{h} \qquad (12)$$



Roof absolute acceleration can be estimated assuming the building acts as a single-degree-of-freedom nonlinear oscillator with an elastic-perfectly-plastic pushover curve, using the N2 method proposed by Fajfar (1999). Its elastic period can be taken from the mean suggested by Chopra and Goel (2000) in the case of steel or concrete; from Camelo et al. (2001) in the case of timber; or from ASCE 7

(2010) or local guidelines where these sources do not apply. Its strength can be estimated from the unfactored design strength specified by local design requirements.

3.6 BUILDINGS COLLAPSE EFFECTS

Another effect that contributes significantly in non-structural damage and consequently their repair cost is building collapse. So far, the methodology has considered non-structural components individually and separate from any building collapse effect. However, studies have shown that building collapse can have significant increasing consequence on non-structural damage and repair cost (Taghavi & Miranda 2003).

Therefore, the presented methodology considers the collapse effect by applying the probability of collapse of the index building at each level of x using the following equation;

$$P_c(x) = \varphi\left(\frac{\ln(\frac{x}{\hat{S}_{CT}})}{\beta_{TOT}}\right) \tag{13}$$

Where:

$\hat{S}_{CT}$= median collapse capacity of the building in terms of Sa(T,5%) and β_{TOT} denotes the total logarithmic standard deviation of the collapse capacity. The user can calculate both values by methods specified in D'Ayala and Meslem (2012), or by FEMA P-695, or by the following simplified method based on FEMA P-695.

$$\hat{S}_{CT} = C_s \cdot 1.5 \cdot R \cdot CMR \cdot SSF \tag{14}$$

$$\beta_{TOT} = 0.8 \tag{15}$$

Where:

C_S = seismic response coefficient (see below for example of how to calculate C_S in the United States). Note that it is defined as $C_S = V/W$, i.e., design base shear as a fraction of building weight, but in the US is calculated as shown later. It may be calculated in other ways in other countries.

V = design base shear, units of force

W = building weight

R = response modification factor, essential ductility demand at design-level ground motion. Can be taken from ASCE 7-10 Table 12.2-1 (duplicated in Appendix C) or from local standards.

CMR = collapse margin ratio, as defined in FEMA P-695: "The ratio of the median 5%-damped spectral acceleration of the collapse level ground motions, $\hat{S}_{CT}$ (or corresponding displacement, S_{DCT}), to the 5%-damped spectral acceleration of the MCE ground motions, SMT (or corresponding displacement, SDMT), at the fundamental period of the seismic-force- resisting system." In the US, ordinary buildings are designed to resist base shear of $2/3 \cdot SMT/(R/I_e)$, where I_e is an importance factor, generally though not always 1.0, and R is as defined above.

Default values for CMR:

= 1.0 for unreinforced masonry or earthen structure

= 1.5 for special reinforced concrete moment frame

= 2.0 for others

SSF = spectral shape factor, as defined in FEMA P-695. Default value = 1.15

For example, in the U.S., one could calculate CS from ASCE 7-10 Sec 12.8.1.1, as follows:

$$C_s = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)} \tag{16}$$

Finally, calculate the expected value of the nonstructural repair cost as a fraction of the total building replacement cost new, at each value of x as follows, where RCN is the replacement cost (new) of the building, N is the number of stories, f_1 is the fraction of total building replacement cost (new) represented by nonstructural components, and f_2 is the fraction of total building replacement cost (new) represented by nonstructural components in the inventory.

$$y(x) = P_c(x) \cdot f_1 + (1 - P_c(x)) \cdot \left(\frac{\frac{f_1}{f_2} \cdot \sum_{h=1}^{N} E[C|S_h = s_h(x)]}{RCN} \right) \tag{17}$$

3.7 SIMPLIFIED NONLINEAR STRUCTURAL ANALYSIS METHOD

The most accurate structural analysis method to derive structural response of buildings is three dimensional nonlinear dynamic analysis. The nonlinear structural analysis is used by the ATC-58 methodology to calculate structural response and consequently, to calculate repair cost of building components. However, despite the high accuracy of the nonlinear dynamic analysis used by ATC-58, it takes long, days or more to create and analyze the necessary structural models.

As mentioned in Chapter 2, in "Nonlinear analysis method for performance based seismic design" by Peter Fajfar [2000], a simplified method for nonlinear seismic analysis of structures is introduced (N2 method). The Fajfar method still requires structural analysis, which can take hours or days to set up for a single building. In this work, a new simplified structural analysis is introduced and mentioned above. In the simplified method, a building is assumed as a single degree of freedom system that performs as a cantilever beam.

CHAPTER IV

ILLUSTRATIVE EXAMPLES

The index building used to exemplify the methodology is the Business School at the University of Colorado at Boulder. The building is close to the M.120 building model in RSMeans Square Foot Cost (2009) construction cost manual in the United States. The M.120 building model represents a lowrise, concrete shearwall building category with an educational occupancy.

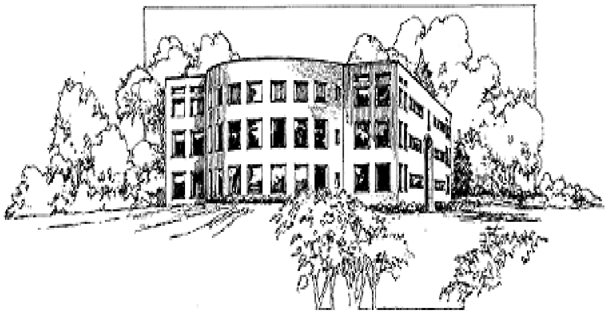


Figure 2. Business school at the University of Colorado at Boulder. And Figure 3. RSMeans building model M.120

The building information is mentioned in the Table 1.

Table 1. CU business school building information

Building name:	CU Business school	Building type:	shearwall, Low Rise, Educational	Ie (SRC=II)	1
location:	US	Building model	M.120	Fa	1.2
No. of Story:	3	height category:	Low rise	Ss(Boulder)	0.25
Story height (ft.):	12	Lateral Force Resisting System (shear wall=SW, Frame=FR, Linear=LN)	SW	Sms=Fa*Ss	0.3
Occupancy	educational	Installation quality (Poor=P, Typical=T, Superior=S)	T	Sds=(2/3)Sms	0.2
Design era:	2009	qc (median structural collapse capacity)	0.518	Cs=Sds/(R/I)	0.04
Construction era:	2009	bc(logstdev of collapse capacity)	0.8	Cs >= 0.044*SDS*Ie, Cs >= 0.01	0.01
Structural material:	steel	Cs	0.04		
Labor as fraction of total repair cost	0.5	R	5		
Local labor cost/PACT labor cost	1.0	CMR = collapse margin ratio, as defined in FEMA P-695. Default values: 1.0 for unreinforced masonry or earthen structure, 1.5 for special reinforced concrete moment frame, 2.0 for others	1.5		

Before we go through the process of deriving the vulnerability of non-structural components of the building using the proposed methodology, one needs to quantify structural response of the building. By structural response, one means story drifts and floor accelerations for all stories and floors of the building, as a function of base excitation measured in terms of Sa(1 sec, 5%). I want to be able to create vulnerability functions in hours or days, including all of the other work required so in this work, and as introduced in previous section by Equations 7,8 and 9, I use an extremely simplified approach that does not require structural analysis.

For the current example, the idealized shear wall mode shape is used to calculate the drift and acceleration distribution as mentioned in the above section. I used the shear wall mode shape because the building structural type is close to concrete shear wall. The benefits of the approximate approach that it is fast and easy to apply. Also, in this example we use roof acceleration excitation equal to s=1 g.

The shear wall mode shape function for our example, h=36ft and x=12 (first floor), is follows:

$$\frac{w(12)}{w(36)} = \frac{12^2}{36^5}\frac{(70 \times 36^3 - 40 \times 36^2 \times 12 + 5 \times 36 \times 12^2 + 2 \times 12^3)}{37} = 0.17$$

Therefore, for our three stories example building, the mode shape is the following vector;

$$\varphi_{m,displacement}(X) = \begin{Bmatrix} 0.17 \\ 0.55 \\ 1.00 \end{Bmatrix}$$

The building period, T, and the modal participation factor, Γ, are as follows:

$T = 0.0488 \times H^{0.75} = 0.717\ sec$

$\Gamma = \frac{0.17+0.55+1.00}{0.17^2+0.55^2+1.00^2} = 1.29$

The first story drift for $S_a(1\ sec, 5\%) = 1g$ and $\Gamma = 1.29$ and T=0.717 and g=32.2 ft/s^2 based on Equation 8 is:

$$S_{PTD,1}(1g) = 1.29 \times 1 \times 32.2 \times \frac{0.717^2}{4\pi^2}\left(\frac{0.17-0}{12-0}\right) = 0.0078$$

Similarly, floor accelerations can be derived using the floor acceleration distribution function for shear wall building. As an example, for the first story, the acceleration value after substituting PGA=$0.4 \times S_a(1\,sec, 5\%)$, (ASCE 7-10) is:

$$S_{PFA,1}(1g) = 0.4 \times 1 + 0.17 * (1.29 \times 1 - 0.4 \times 1) = 0.55$$

Therefore, the final structure response vector at $S_a(1\,sec, 5\%) = 1g$ is;

$$S_m(X) = \begin{Bmatrix} 0.0078 \\ 0.017 \\ 0.020 \\ 0.4 \\ 0.55 \\ 0.89 \\ 1.29 \end{Bmatrix}$$

4.1. STEP 1: SELECT INDEX BUILDING AND IDENTIFY TOP NON-STRUCTURAL COMPONENTS

The building is low-rise reinforced concrete shearwall building used for education. The top non-structural components with respect to repair cost can be derived from the RSMeans Square Foot Cost (2009) manual. The resulting components and their rankings for the building model are shown below. Note that each component is also mentioned by its NISTIR classification code shown in the classification row.

Table 2. Ranking of nonstructural components in decreasing order of contribution to construction cost

	Ranking of nonstructural components in decreasing order of contribution to construction cost						total nonstructural construction cost (sf) $	% of total nonstructural construction cost
rank	1	2	3	4	5	6	104.29	0.56
component name	Terminal & package units	Plumbing fixtures	Lighting & branch wiring	Partitions	Interior Doors (Partitions)	Exterior Windows (Curtain walls)		
classification	D3050	D2010	D5020	C1010	C1020	B2020		
square ft. cost ($)	18.2	13.31	11.7	6.83	4.34	3.98		

The top components participation in construction costs is illustrated in table 3.

Table 3. Top components participation in construction costs

Total Construction cost ($)	Construction cost per Sq. Ft ($)	% of total construction cost	Total non-structural construction cost ($)	% of total non-structural construction cost
126.72	$ 58.40	46%	$ 104.29	56%

Corresponding demand parameters and installation quality are illustrated in Table 4.

Table 4. Demand parameter of the top components

Components' classification based on installation quality:					
D3052.011d	0	C3032.00b	C1011.001d	C1011.001d	B2022.035
Demand parameter (Peak Floor Acceleration=PFA, Peak Transient Drift=PTD)					
PFA	PFA	PFA	PTD	PTD	PTD

Note that we will use the right value above called "% of total non-structural construction cost" later as the scale-up value, F(m), in our calculations.

4.2 STEP 2: DERIVING COMPONENT VULNERABILITY FUNCTIONS

The sample calculation has been done based on the equations mentioned above in the proposed methodology section by using roof acceleration excitation equal to s=1 g. Also, we picked the partition component C1011.001d as the non-structural component for our sample calculation.

As we saw in the methodology section, to derive the component level vulnerability function, one can use the equation below;

$$E[C \mid S = s, H = h] = \sum_{i=1}^{N_i} \sum_{d=1}^{N_d} P[D_i = d \mid S = s] \cdot E[C \mid D_i = d] \cdot W_h(i) \qquad (2)$$

In our example;

C: In our case the currency is US dollars.

S: For our sample calculation, s=1 g and the whole calculations are using that excitation value.

H: we used partition component C1011.

i: 1, since one component category is picked as a representative of the all categories of the component.

N_i: 1

d: In this case it can be damage state 1, 2 or 3. (DS1, DS2 and DS3)

N_d: In this case and for wall partition is 2.

$W_h(i)$: 1 since we only choose one component.

$E[C\ |D_i = d]$: For the partition component C1011.001d, the values for damage states 1, 2 are illustrated in Table 6 below as median (P50) repair cost by damage state.

The values of the fragility function parameters for the partition component C1011.001d are shown in the tables 5 and 6, which are derived directly from ATC-58 database.

Table 5. Partition nonstructural component specifications

Component Specifications			
Component No.:	4	Comp. name	Partitions
Probability of usage:	1	Unit	Each (13'x100' Panel)
Demand parameter	PTD	Reference	PACT Beta 1.0
NISTIR Classification	C1011.001d		

Table 6. Top components fragility and repair cost functions parameters

Fragility function		
Damage state	Median	Beta
1	0.0035	0.7
2	0.0093	0.45
3	0	0
Repair cost by damage state		
Damage state	P50	Beta
1	5099.997	0.397
2	19762.509	0.096
3	0	0

Therefore, component level vulnerability calculation becomes as below;

$$E[C\ |S = 1g, H = C1011] = [0.53 \times 5100 + 0.34 \times 19762] \times 1.00 = \$9.76 \times 10^3$$

Where the probabilities of being in each damage state (for the first floor and $S_a(1\ sec, 5\%)$=1g; PFA= 0.4 and PTD= 0,0078) are as follows:

$$P[D_i = 1\,|S = 1g] = \Phi\left(\frac{ln\left(\frac{0.0078}{.0035}\right)}{0.7}\right) - \Phi\left(\frac{ln\left(\frac{0.0078}{.0093}\right)}{0.45}\right) = (0.87 - 0.34) = 0.53$$

$$P[D_i = 2\,|S = 1g] = \Phi\left(\frac{ln\left(\frac{0.0078}{.0093}\right)}{.45}\right) = 0.34$$

Similarly, component level vulnerabilities for other components and their quantities are as follows.

Table 7. Drift sensitive components unit repair cost and quantity

	unit repair cost	Quantity (Q)	Unit
Partition	0.9	1.2	600 SF
interior doors	9.76E+03	30	Each (13'x100' Panel)
exterior windows	9.76E+03	25	Each (4'x8' Panel)

Below is the component level fragility function for partition including its two damage states separately.

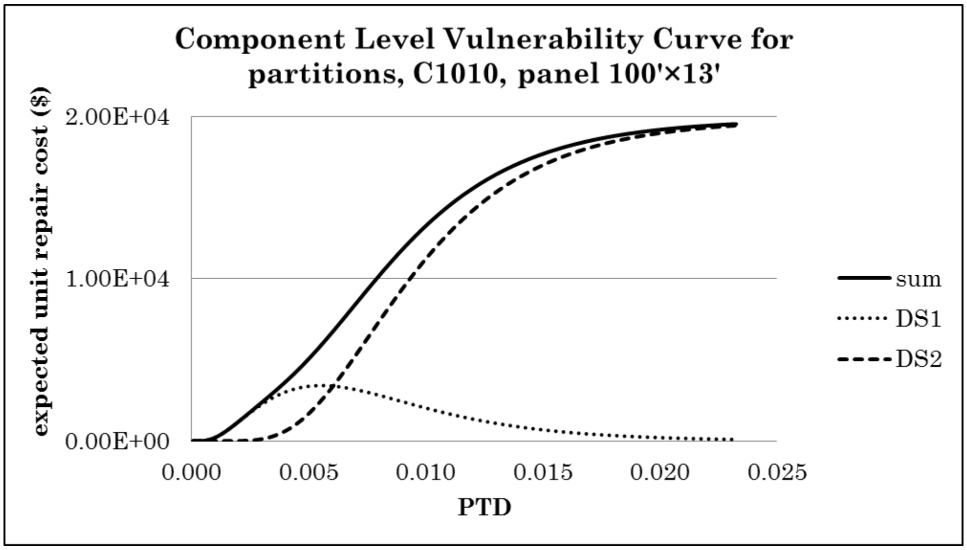


Figure 4. Component level vulnerability function for partitions, C1010, panel $100' \times 13'$.

4.3 STEP 3: DERIVING STORY-LEVEL NONSTRUCTURAL COMPONENT VULNERABILITY FUNCTIONS

We derive story level vulnerability for drift sensitive components and acceleration sensitive components separately. Therefore, for components sensitive to peak transient drift (partitions, interior doors and exterior windows);

$$E\left[C_{PTD,n} \,\middle|\, S_{PTD} = 0.0078, M = 120\right] = (9.76 \times 10^3 \times 1.2) + (9.76 \times 10^3 \times 30) + (0.9 \times 25) = \$292743$$

For component sensitive to peak floor acceleration, the components quantities and repair cost values are as follows;

Table 8. Acceleration sensitive components unit repair cost and quantity

	unit repair cost	Quantity (Q)	unit
Terminal & package unit	1.72×10^5	2	Each
Plumbing fixtures	0	70	Each
Lighting & branch wiring	2.51×10^2	40	600 SF

Note that plumbing fixtures are assumed to be non-damageable, and as a result their repair cost is zero. However, they still have contribution to the construction cost of the top nonstructural components.

Therefore, the story level vulnerability for acceleration-sensitive components is;

$$E\left[C_{PFA,n}\,\middle|S_{PFA,n} = 0.0078, M = 120\right] = (1.72 \times 10^5 \times 2) + (0 \times 70) + (2.51 \times 10^2 \times 40) = \$353426$$

4.4 STEP 4: BUILDING-LEVEL NON-STRUCTURAL COMPONENTS VULNERABILITY FUNCTION

For the building level vulnerability, the building analysis results that are determined before are used. The analysis results are as follows.

Table 9. The building analysis results

T (sec):	0.294
w (rad/sec):	21.376
Γ:	1.291
g (ft/sec^2):	32.174

Therefore, the building level vulnerability function is as below;

$$E[C\ |M = 120\ , X = 1\ g] = \frac{[(292743 + 353426) + (557385 + 40242) + (576093 + 178579)]}{0.56} = \$3568864$$

Where the number of stories in our case is 3. The other parameters were derived in previous steps.

Therefore, the damage factor is the expected repair cost divided by the total construction cost;

$$DF[C\ |M = 120\ , X = 1\ g] = \frac{3568864}{9123840} = 0.39$$

The result index building vulnerability curve is as below;

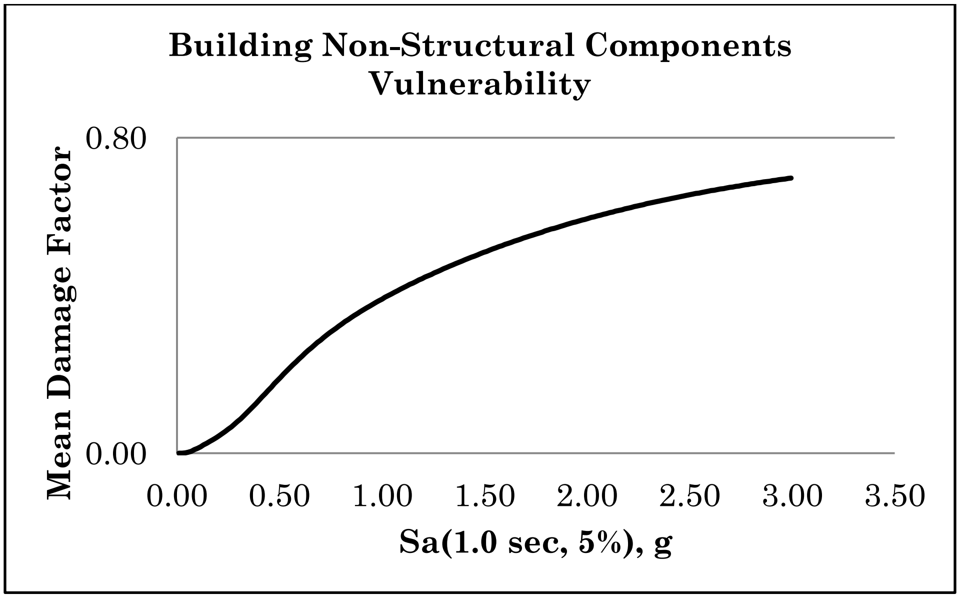


Figure 5. Building Non-Structural Components Vulnerability

4.5 BUILDINGS COLLAPSE EFFECTS

Let's Calculate the collapse probability at each level of x.

Where

R = 5 (According to the ASCE7-10 for the building structural type)

CMR = 2.0

SSF = 1.15

$C_s = 0.04$ (ASCE 7-10 Sec 12.8.1.1)

$$\hat{S}_{CT} = 0.04 \cdot 1.5 \cdot 5 \cdot 2.0 \cdot 1.15 = 0.69$$

$\beta_{TOT} = 0.8$

$$P_c(x) = \varphi\left(\frac{\ln(\frac{1}{0.69})}{0.8}\right) = 0.68$$

Finally, calculate the expected value of the nonstructural damage factor at each value of x as follows;

$$y(1g) = 0.68 \cdot 0.56 + (1 - 0.68) \cdot \left(\frac{\frac{0.56}{0.46} \cdot (1998563)}{9123840} \right) = 0.52$$

After considering the building collapse effect into the vulnerability graph or function for the building, the resulting graphs considering both non-collapse and collapse considerations are as follows.

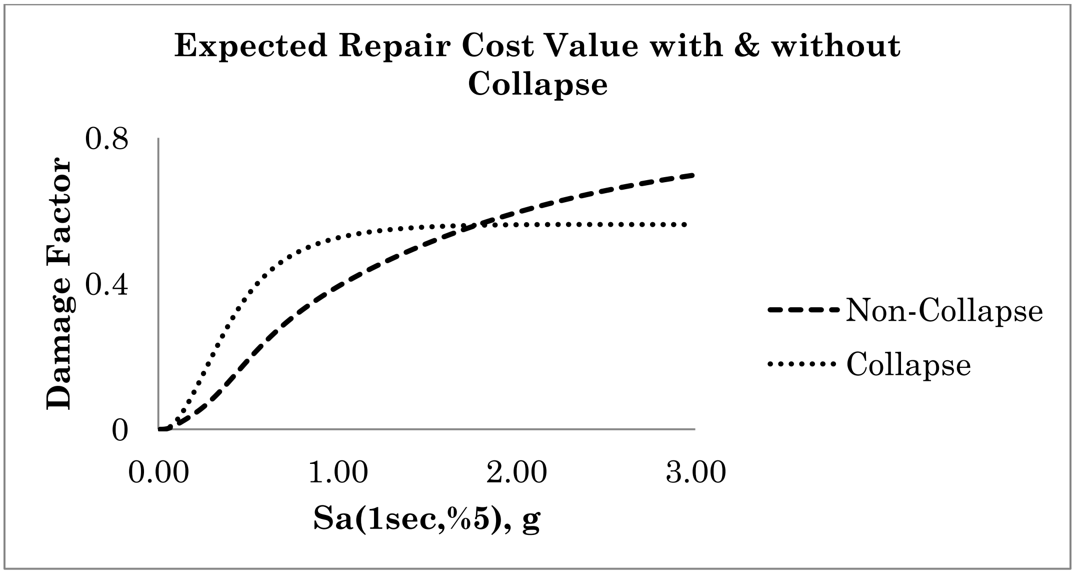


Figure 6. Building Non-Structural Components Vulnerability for non-collapse and collapse situations

4.6 VALIDATION

To check the validity of the result, I have compared it with the results of HAZUS-MH and ATC-13 vulnerability functions for whole buildings. The HAZUS-MH has vulnerability functions for lowrise, concrete shearwall educational building. Also, ATC-13 vulnerability function illustrated below is for lowrise, concrete shearwall educational building. To compare the vulnerability function from this work with the HAZUS-MH and ATC-13 vulnerability functions, I combined HASUZ vulnerability function for structural components with the result of the CU Business school nonstructural vulnerability function. Below is the graph of the three methods and the current work with and without considering building collapse.

The ATC-13 database is based on Moment Magnitude Intensity, MMI, therefore, I transformed the database to make it based on Sa(1 sec, 5%) by using the transformation method introduced by Worden et al (2012).

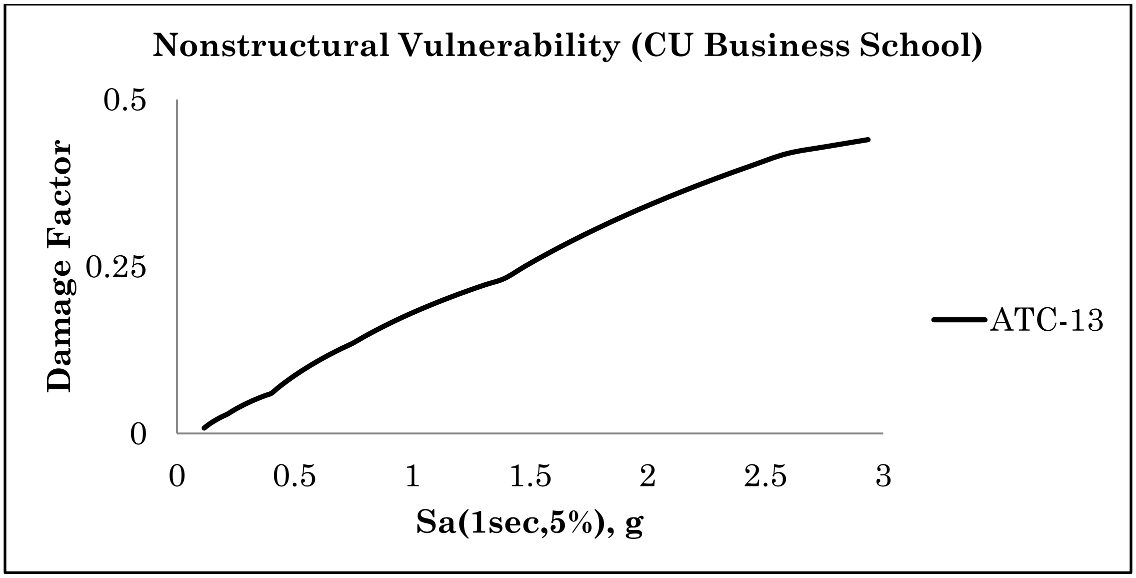


Figure 7. ATC-13 Building Non-Structural Components Vulnerability

Below is the HAZUS-MH vulnerability function for the Business School, including both structural and nonstructural components.

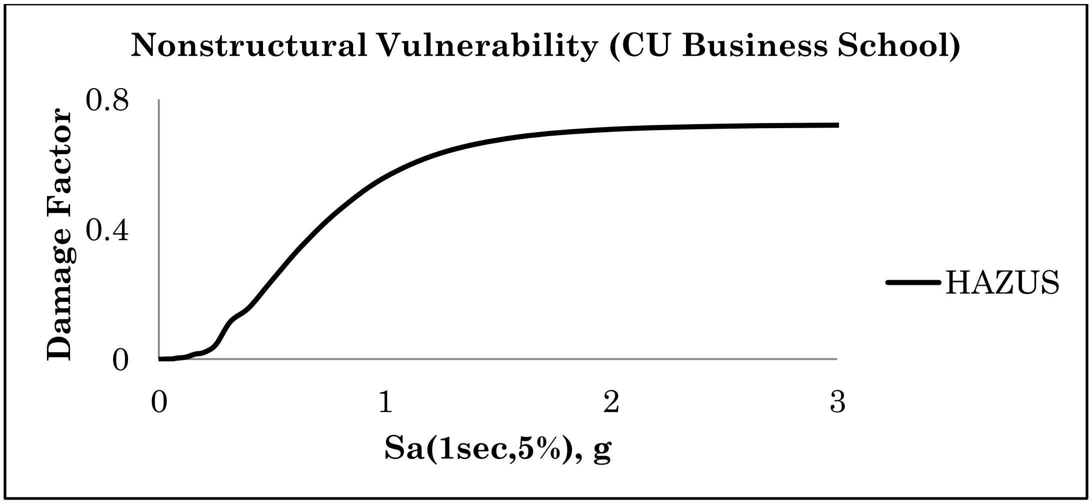


Figure 8. HAZUS Building Non-Structural Components Vulnerability

Below is the combined HAZUS-MH vulnerability function for structural components and the vulnerability function of nonstructural components based on this work (GEM Vulnerability Consortium = GVC (this work), Non-collapse = NC, Collapse = C). The graph below is withut considering the probability of collapse of the whole building.

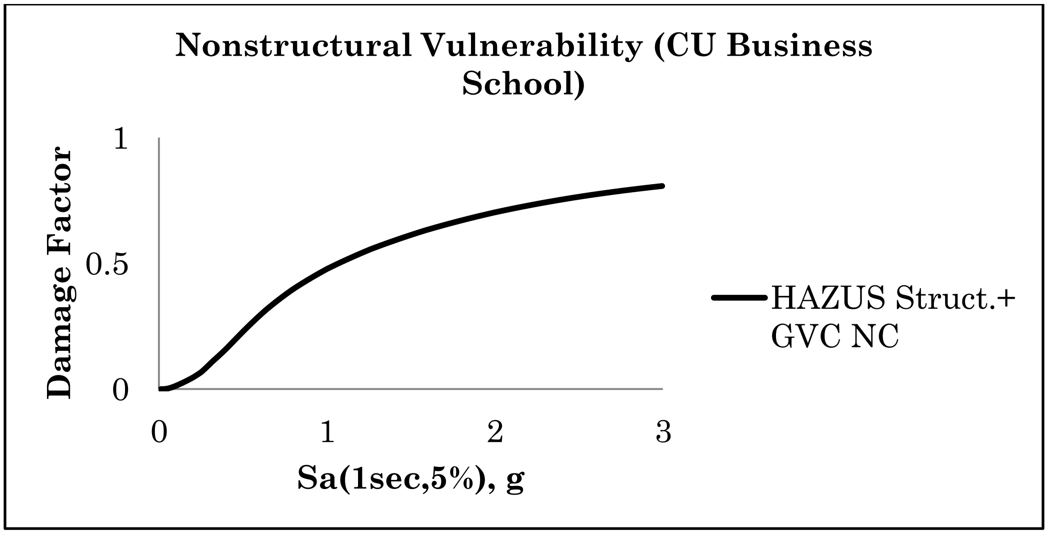


Figure 9. Combined HAZUS Structural and GVC HAZUS Non-Structural Components Vulnerability with non-collapse consideration

Below is the combined HAZUS-MH vulnerability function for structural components and the vulnerability function of nonstructural components based on this work.

In the graph below, the probability of collapse of the whole building is considered.

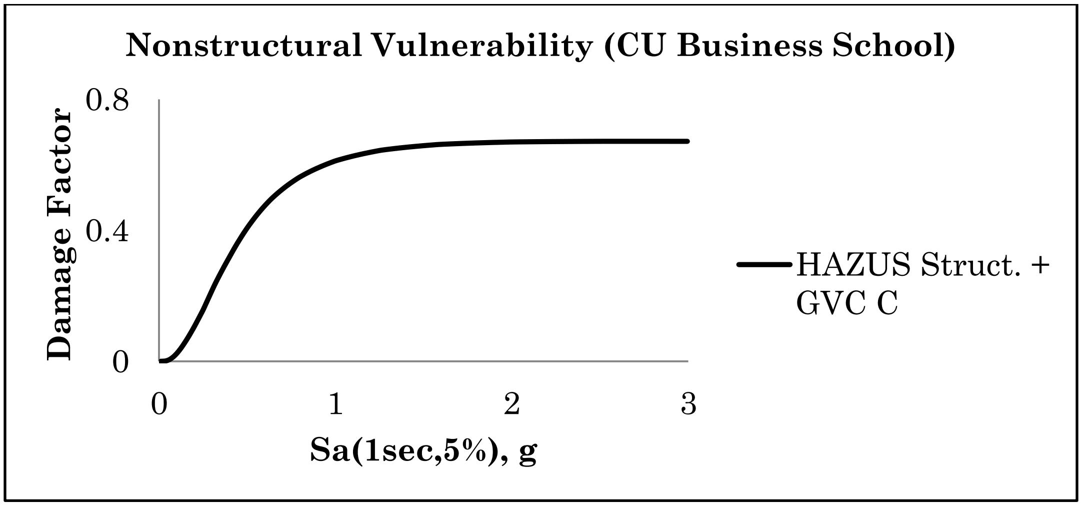


Figure 10. Combined HAZUS Structural and GVC HAZUS Non-Structural Components Vulnerability with collapse consideration

Vulnerability functions from HASUS and ATC-13 are for a building as a whole, including both structural and nonstructural components. Therefore, to compare the vulnerability function of nonstructural components from this work with the vulnerability functions from HAZUS and ATC-13, the result of this work is added to the vulnerability function of structural components provided by HSUS. In Figure 11, the result from this work is added to HASUS vulnerability of structural components of the same building category and is compared with results provided by HAZUS and ATC-13 for a whole building of the same building category.

Below is the illustration of the same graphs above for the sake of comparison. As it is illustrated, there is a good agreement between the results of this work and the result of HAZUS-MH.

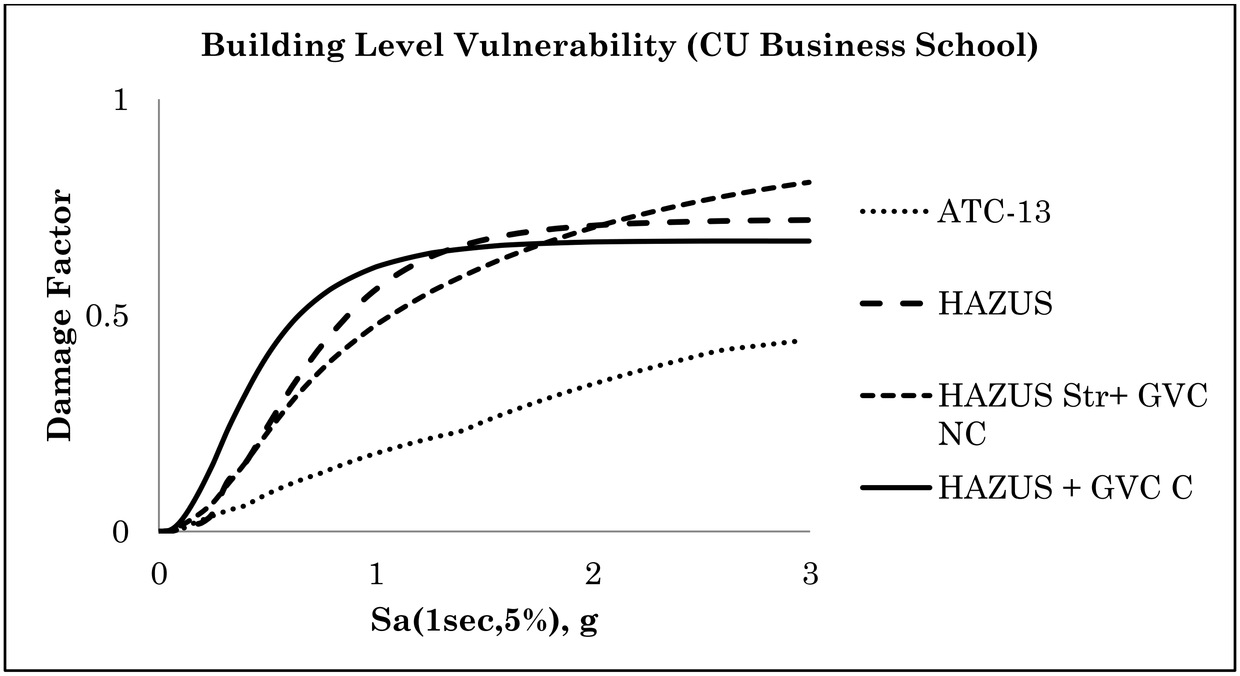


Figure 11. Comparison of non-Structural Components Vulnerabilities from ATC-13, HAZUS and GVC plus HAZUS-Structural components with and without collapse consideration

4.7 RESULTS FOR TWO MORE INDEX BUILDINGS

The second index building is the William Village apartments at the University of Colorado Boulder. The same methodology has been performed on the building to calculate its nonstructural components vulnerability. Below is the nonstructural vulnerability function for the William Village apartments along with the same graph using the other two methods of HAZUS-MH and ATC-13.

The ATC-13 (1985) type is for reinforced concrete shearwall with moment-resisting frame (RC/SW-MRF), highrise (HR, 8+ stories), and reflects both structural and nonstructural vulnerability in a single function. The ATC-13 (1985) authors refer to it as structural class 5. It was derived from a modified Delphi process, drawing on the judgment of 7 experts. The HAZUS-MH (NIBS and FEMA 2009) type is reinforced concrete shearwall, highrise (8+ stories), moderate code (appropriate for a modern building in Colorado), high-occupancy residential use. It was derived analytically, although some of the parameters of the model are likely influenced by the authors' judgment. The "DF" in the HAZUS-MH code means that it gives damage factor as a function off Intensity Measure (IM). For comparison purposes the structural vulnerability function from HAZUS-MH is added to the nonstructural result. All of the ATC-13 and HAZUS-MH data is obtained from Professor Keith Porter, by personal communication. He got them from ATC-13 (1985) directly or from Porter (2009).

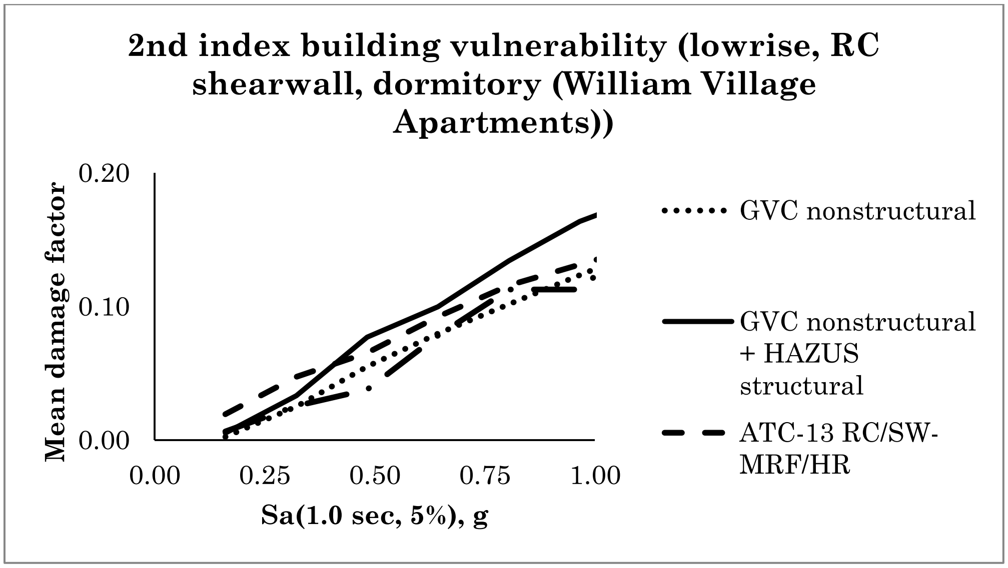


Figure 12. Comparison of non-Structural Components Vulnerabilities from ATC-13, HAZUS and GVC plus HAZUS-Structural components for shearwall building mode shape, William Village Apartment

Below are the results for the vulnerability functions of the same building by using different formulas for mode displacement distribution as described in Chapter

3. Graph 7 is based on shearwall drift distribution. The first graph below is based on linear shape displacement distribution and the latter one is based on frame mode displacement distribution.

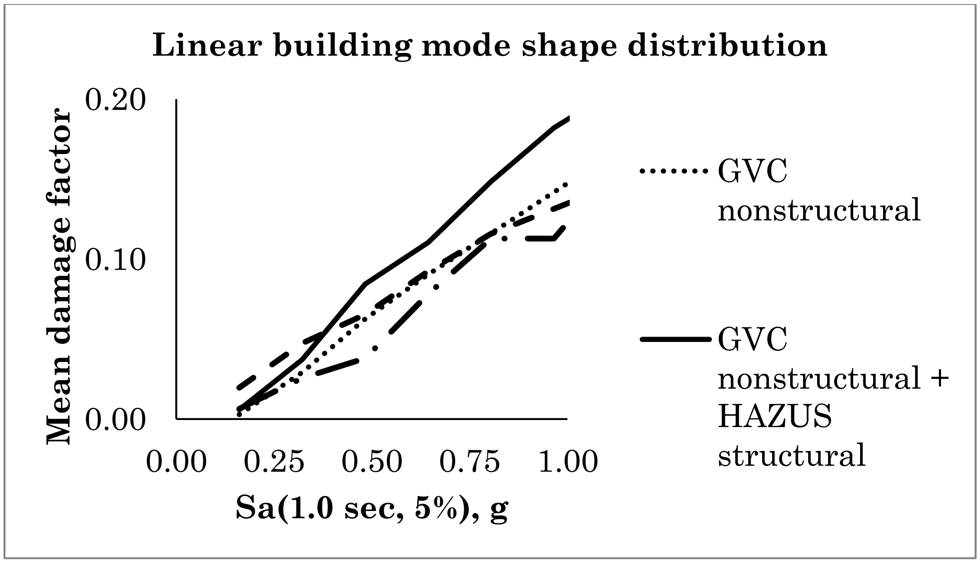


Figure 13. Comparison of non-Structural Components Vulnerabilities from ATC-13, HAZUS and GVC plus HAZUS-Structural components for linear building mode shape, William Village Apartment

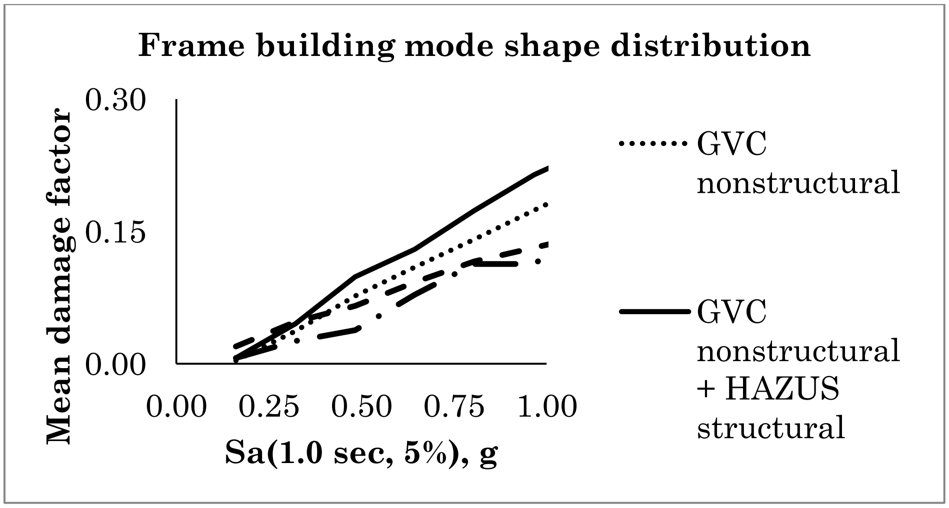


Figure 14. Comparison of non-Structural Components Vulnerabilities from ATC-13, HAZUS and GVC plus HAZUS-Structural components for frame building mode shape, William Village Apartment

The third index building is a building in Shiraz, Iran. The building is a 4-story concrete shearwall. The building information and the resulting nonstructural vulnerability graph are as follows.

Table 10: Shiraz building information

Building name:	Shiraz
location:	Shiraz, Iran
No. of Story:	4
Height:	10 ft
Occupancy	residential
Design era:	2012
Construction era:	2012
Structural material:	concrete

Below is the nonstructural vulnerability function for the Shiraz building.

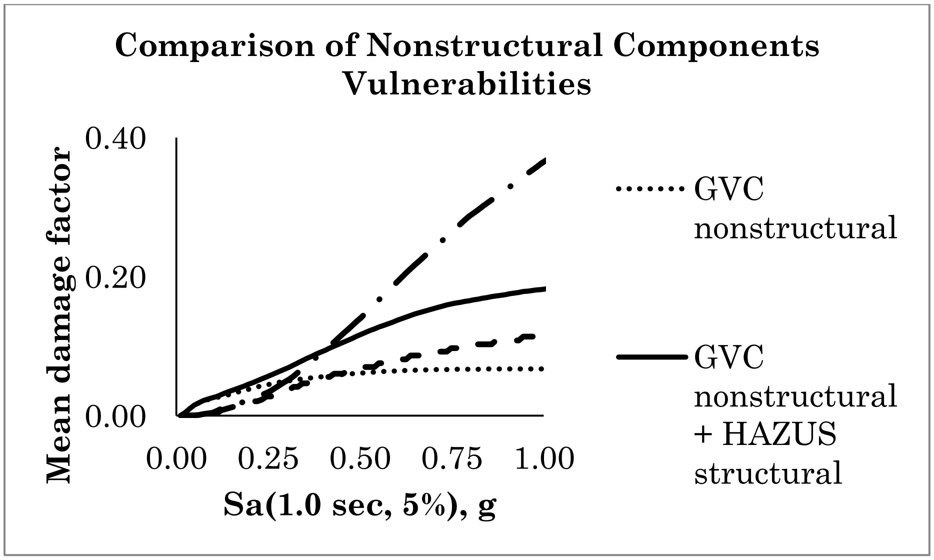


Figure 15. Comparison of Nonstructural Components Vulnerabilities from ATC-13, HAZUS and GVC plus HAZUS-Structural components, Shiraz Building

4.8 SURVEY ON THE MOST COMMON NONSTRUCTURAL COMPONENTS FOR SAMPLE BUILDINGS AT THE UNIVERSITY OF COLORADO AT BOULDER

The second approach for determining the probability of usage to determine weight, W(i) of nonstructural components was assessment of architectural drawings. The current survey has been done on sample buildings at the University of Colorado at Boulder. The sample Buildings are the business school, the Stearns Towers dormitory and the H. G. Woodruff Cottage residential building located at the University of Colorado at Boulder. The buildings selection was based on the idea of choosing buildings with different occupancies and types within the campus.

The top nonstructural components in terms of construction cost considered in the survey were based on the building occupancy types as follows. References to the RSMeans Square Foot Cost (2009) are for its 2010 square-foot cost manual.

Business school: (RSMeans Square Foot Cost (2009) category: M.120: College, Classroom, 2-3 Story)

1) terminal and package units
2) plumbing fixtures
3) lighting and branch wiring
4) partitions

The Stearns Towers dormitory: (RSMeans category: M.130: College, Dormitory, 2-3 Story)

1) plumbing fixtures
2) exterior walls
3) terminal and package units
4) lighting and branch wiring

The H. G. Woodruff Cottage 212 residential building: (Spon's European Construction Cost Handbook, 2000)

1) external walls
2) partitions and internal walls
3) windows and external doors
4) heating and ventilation

Structural and architectural drawings were examined at the Office of Planning Design and Construction located in the Research Laboratory No. 2 Building (RL-2) on the East Campus of the University of Colorado. Also, quantity takeoff from the drawings was conducted.

Some nonstructural types and the installation technique for each type was clear in the architectural and MEP drawings. Therefore, the probability of usage for those nonstructural types can be easily determined using the drawings.

However, during the survey, the large number of nonstructural components for each building and the lack of data for the number of some components used in each building were observed. Therefore, determining the probability of usage for all nonstructural types was difficult.

According to building occupancy study and the highest and the most common construction cost components, the non-structural cost ranking is as follows:

1 electrical installation
2 external works
3 heating & ventilation installation
4 windows & external doors
5 external walls
6 waste oil & overflow pipes, hot & cold water services

The non-structural components cost with respect to building occupancy is as follows. Also, the WHE-PAGER construction types were matched and tabulated with RSMeans Square Foot Cost (2009) construction types and non-structural component cost ranking for each matched type was extracted.

Non-structural cost ranking based on building occupation types is as follows: (Spon's Budget Estimating Handbook, 2nd edition)

Table 11: Non-structural cost ranking based on building occupation types

Factory:	Warehouse:
1) drainage & external works	1) windows & external doors
2) heating installation	2) external works
3) external walls	3) external walls
4) electrical installation	4) electrical installation
Offices:	Supermarket:
1) windows & external doors	1) special services installation
2) external works	2) electrical installation
3) external walls	3) external works
4) electrical installation	4) heating & ventilation installation
Public House:	Health Center:
1) external works	1) heating installation
2) fittings	2) electrical installation
3) heating & ventilation, hot & cold water, waste soil & overflow pipes	3) fittings
4) electrical installation	4) special service installation
Nursing Home:	Housing:
1) external works	1) external walls
2) fittings	2) partitions & internal walls
3) electrical installation	3) windows & external doors
4) windows & external doors	4) heating & ventilation
Garage:	Middle school:
1) external works	1) external works
2) windows & external doors	2) external walls
3) floor finishes	3) heating installation
4) electrical installation	4) electrical installation
Bank:	Court:
1) external walls	1) waste oil & overflow pipes, hot & cold wa
2) hot & cold water system, heating installation	2) electrical installation
3) windows & external doors	3) drainage, external works
4) electrical installation	4) fittings
Ambulance station:	Hotel:
1) external works	1) waste oil & overflow pipes, hot & cold water services, heating & ventilation
2) sanitary fittings, waste oil & overflow pipes, hot & cold water services, heating	2) external walls
3) windows & external works	3) electrical installation
4) partitions & internal walls	4) drainage & external works
Student hostel:	
1) electrical installation	
2) heating installation	
3) windows & external doors	
4) external walls	

4.9 HOW TO GET REPAIR COST OF NON-STRUCTURAL COMPONENTS IN THE ABSENCE OF SUCH DATA OR LACK OF CONSTRUCTION COST MANUALS

Much of the foregoing employs the ATC-58 library of consequence functions from its PACT software. These consequence functions give repair cost given a detailed component type and damage state, and provide costs in US dollars, assuming the repairs take place in the United States. But the present methodology is intended to be applicable elsewhere in the world as well. In the case that there are no repair cost data available, one can contact local building contractors and ask them about such data. For that, one should describe the exact component type, size and capacity to the contractor who works on the same field of building construction. Also, one needs to describe the possible component damage states, and then he can ask the contractor about the cost to repair the component in a building model in that region.

4.9.1 CASE STUDY OF: HOW TO GET REPAIR COST OF NON-STRUCTURAL COMPONENTS IN THE ABSENCE OF SUCH DATA OR LACK OF CONSTRUCTION COST MANUALS

As an example, we choose the building in Shiraz, Iran. The building is a 4 story shear wall concrete with residential occupancy. There is no documented manual available for determining repair cost of non-structural components. After listing the exact type, size and capacity and damage states of the components to run the methodology, I contacted a contractor who works in the same field of work and asked them about the cost they would ask to repair damaged components.

Below is the summary of the information and data I received from the contractor:

Table 12. Shiraz building information

Notes:		
	DS: damage state (eg. DS1= damage state 1)	
	NA: Not Applicable	
	RC: Regional Currency	
Building information:		
	Location:	Shiraz, Iran
	No. of Story:	4
	Height:	12.2 m
	Occupancy:	residential
	Design era:	2012
	Construction era:	2012
	Structural material:	Concrete
	Regional currency:	IRR (Iranian Rial)

In Appendix C, the regional nonstructural repair cost questionnaire is provided with the top 5 nonstructural components for the building model corresponding to the Shiraz building. In the questionnaire, a general contractor is asked to provide repair cost per specific quantity of the top five components and relevant damage states.

4.9.2 SURVEY RESULT

In this survey, the construction contractor for the building in Shiraz, Iran, was contacted and was interviewed. In the interview, he was introduced to the goal of this methodology and the top five components. Next, he was asked about his description of damage states of the top nonstructural components. Table 13 and 14 are the result of the survey with the description of damages states.

Table 13. Top nonstructural components and damage states descriptions for the Shiraz building

No.	Component	Component description	DS1 description	DS2 description	DS3 description
1	energy supply	water heater	The water heater internal connections are leaking	The electrical motor and the storage are damaged and should be repaired	The Electromotor is damaged and should be replaced
2	elevators & lifts	cable traction elevator	The fuses damaged, small electrical conflicts occurs	Small parts like electrical sensors or hydrolic jacks are damaged	The main board is damaged or the Electromotor is completely damaged and shoud be replaced
3	exterior walls	Full-height width hollow clay blocks with cement mortar and finishing	few shallow cracks on painting and finishing and needs to be repainted	few tiny but deep cracks through the partition depth but still repairable by new finishing and painting	several deep and wide cracks all over the wall and the whole partition needs to be demolished
4	partitions	Half-height hollow clay blocks with gypsum mortar and finishing	few shallow cracks on painting and finishing and needs to be repainted	few tiny but deep cracks through the partition depth but still repairable by new finishing and painting	several deep and wide cracks all over the wall and the whole partition needs to be demolished
5	interior doors	interior wooden door	The door frame is slightly moved outside and crackes are appeared on the supported walls	The door frame twisted and the hinges are damaged and needs to be replaced	The door and the frame is cracked and needs to completely replaced
6	cooling generating system	Water based cooler	The water pump is damaged	The cooler doors are damaged and the cooler box needs to be replaced	The cooler electro motor is damaged and electrical system of the cooler and the cooler box should be replaced

The construction contractor for the Shiraz building was also asked about the repair cost including material cost and labor cost. The costs are in regional currency (RC), which is Iranian Rial in this case. The data below is provided by one contractor as an example and one can ask several contractors within the field to obtain more reliability on data.

Table 14. Top nonstructural components repair cost based on material cost and labor cost

No.	Component	Component description	Labour hours DS1	Labour hours DS2	Labour hours DS3	Regional labour cost/hour (RC)	Material repair cost/unit (RC)	Material unit
6	energy supply	water heater	1	2	2	150000	5000000	one unit
1	elevators & lifts	cable traction elevator	0.5	1	3	100000	7500000	one unit
2	exterior walls	full length width hollow clay blocks with cement mortar and finishing	0.5	1	2	30000	2.00E+05	m^2
3	partitions	half-length hollow clay blocks with gypsum mortar and finishing	0.2	0.5	1	30000	100000	meter
4	interior doors	interior wooden door	1	2	2	50000	3000000	one unit
5	cooling generating system	Water based cooler	0.5	1	1	100000	8000000	one unit

4.10 CASE STUDY: HOW TO DETERMINE PROBABILITY OF USAGE OF NONSTRUCTURAL BUILDING COMPONENTS FROM LOCAL CONSTRUCTION MATERIAL STORE

As mentioned in chapter 3, probabilities of usage or weighting items in Equation 1, $W_h(i)$, can be determined from the relative amount or number of usage of a nonstructural component of each size or capacity sold recently in a local construction material store. The table below is a sample result of the survey performed at the HomeDepot local store in Boulder, Colorado. The table is for partitions as the sample component category. The full survey result is illustrated in Appendix B. By dividing the number or amount of the specific item size or capacity they have sold within a year by the total number or amount of the same nonstructural type but different sizes or capacities, one can calculate the probability of using of that specific item.

Table 15. Nonstructural probability of usage from local store

Nonstructural probability of usage survey			
Type:	Wall Partition, Type: Gypsum		
Total number of the type sold	611		
Selling time period	One week		
No.	Item description	Number sold	Probability of usage
1	1/2"x4'x8'	342	0.56
2	5/8"x4'x12'	5	0.01
3	1/2"x4'x8' (moisture resistant)	93	0.15
4	1/4"x4'x8'	30	0.05
5	5/8"x4'x8'	141	0.23

CHAPTER V

FINDINGS AND RESULTS

5.1 HOW LONG WILL RUNNING THE METHODOLOGY TAKE?

As it is mentioned in the introduction, one of the main objectives is to design the methodology so that it can be feasibly applied within a short period of time. Once all of the required information related to the building has been collected and evaluated, it will take a couple of hours to determine the vulnerability of the nonstructural components of the building. The most time-consuming step throughout the whole process is to calculate the quantity of each top nonstructural component in a building. According to the experience of the author, based on the components and building size, it takes couple hours to take off the required quantities from the building drawings. However, sometimes there is a lack of fragility functions or repair cost value for one or more of the top components. In that case, the user might spend some more time trying to find the best alternative component to replace the missing function.

5.2 REQUIRED SKILLS TO APPLY THE METHODOLOGY:

To run the methodology, the user needs to have enough knowledge of structural behavior and response to understand different sections and their application in the methodology. They key concepts that the user needs to know are mode shapes, drift and acceleration distribution of buildings, period, seismic excitations and structural dynamic response. Also, the user needs to have an understanding of various building materials and the effect of height and lateral force resistance systems in response. It is for these reasons the user requires to have a master's degree in structural engineering. This requirement is necessary for the user to have an acceptable interpretation of the methodology and its procedures and the ability to execute the procedures with complete comprehension of the inputs and outputs.

5.3 METHODOLOGY CALCULATION SOFTWARE:

The methodology can be programmed and made accessible in most of the common programming software such as Matlab and Microsoft Excel. In the current work, the entire methodology is organized in a Microsoft Excel worksheet. In the Excel worksheet, one can input the required information and data about the building and rapidly return the building's nonstructural vulnerability function. The details of the input and output of the worksheet are discussed below. The worksheet is going to be uploaded to the GEM website where it will be accessible worldwide.

5.4 THE GUIDANCE FOR GEM VULNERABILITY CONSORTIUM NONSTRUCTURAL BUILDING COMPONENTS VULNERABILITY CALCULATION WORKSHEET

The Microsoft Excel worksheet is provided to derive the vulnerability function and graph, i.e. repair cost with respect to seismic excitations, of non-structural building components for different building categories. The calculations in the worksheet are based on the work has been done by the non-structural vulnerability team at the University of Colorado at Boulder for the GEM.

5.4.1 INPUT:

To apply the worksheet, the user must input the minimum required building parameters to derive the vulnerability function. The required input parameters are indicated by the yellow colored cells in the "building info & procedure" tab. The required parameters are as follows:

1) Number of stories
2) Story height (ft.)
3) Building model based on RSMeans Square Foot Cost (2009) Manual
4) Lateral Force Resisting System (Shear wall=SW, Frame=FR, Linear=LN (drift distribution over the height of the building is linear))
5) Total building floor area (sq ft)
6) Quantities of indicated non-structural components at each story

7) Installation quality of non-structural components (Poor=P, Typical=T, Superior=S)

The worksheet automatically uses the 'PACT Beta 1.0 database for the required non-structural building components fragility and repair cost parameters.

The worksheet also uses the absolute roof acceleration, relative roof displacement and the displacement distribution over height derived from simplified linear structural analysis of single degree of freedom oscillator assumption for a building. Therefore, for non-linear applications, the user needs to provide the nonlinear analysis results and input the absolute roof acceleration, relative roof displacement and the mode shape vectors in the designated locations colored yellow in the “Acc.-Drift Distrib.” tab.

5.4.2. RESULT

After entering the required parameters in the yellow cells, the building non-structural components vulnerability curve will be produced automatically at the result section at the bottom of the “building info & procedure” tab. The graph is presented in terms of damage factor, i.e. ratio of non-structural components repair cost to total construction cost of the building, with respect to response spectral acceleration at 1.0 second and 5% damping.

5.5 VALIDATION PROCEDURES

The results obtained from applying the methodology should be verified for their accuracy and acceptability. The following procedures can be used to check the results.

a) Sanity Check**.** In general, the results should satisfy experienced earthquake engineers regarding the total repair cost of non-structural components in a building given the detailed specifications and location of the building. If the results are too far from their opinion, the calculation should be rechecked.

b) Reasonable Sensitivity to Component Quantities. Results should vary if rooms and spaces in a building change. For example, bigger rooms should lead to a smaller total quantity of partitions and therefore to a smaller repair cost for partitions. This research will specify sensitivity tests that can be carried out to check that there is a reasonable sensitivity to component quantities.

c) Reasonable Results Relative to Other Buildings. The results can be compared with buildings with more-fragile or less-fragile non-structural components. The relative vulnerability functions should make sense: the building with less-fragile components should be lower (less loss for the same excitation) than the building with more-fragile components. The research will specify tests versus buildings with existing vulnerability functions that should bracket that of a new vulnerability function.

d) Asymptotes to Total Loss. The total repair cost for high excitations should be close to 100%, i.e., near the total construction cost (new) such as that determined from construction costs manuals. The research will specify tests to check this.

5.6 SENSITIVITY TEST

To have a better understanding of the sensitivity of non-structural vulnerability functions from variation of effective parameters in deriving them, it is necessary to perform a series of sensitivity tests.

The first test is verifying the sensitivity of vulnerability functions on component installation situation. This test measures the difference between the results from fully anchored or isolated component and uninstalled components. The anchorage test was selected because lack of anchorage was the main reason for damage to nonstructural components seen in reconnaissance reports.

The second test is for verifying the effect of using alternate components instead of the top components that contribute most to the repair cost.

The third test is determining the effect of applying more than five components.

The tests' outcomes help us modify the methodology to make it more applicable and practical. As an example, quantifying plumbing fixtures of an entire multistory building is time consuming. If the results of the sensitivity tests show that using alternate non-structural components do not cause a significant difference in the result, and if the next non-structural component is easy to quantify such as external windows, then one can save time and effort deriving the vulnerability function. The results of the three sensitivity tests are as follows;

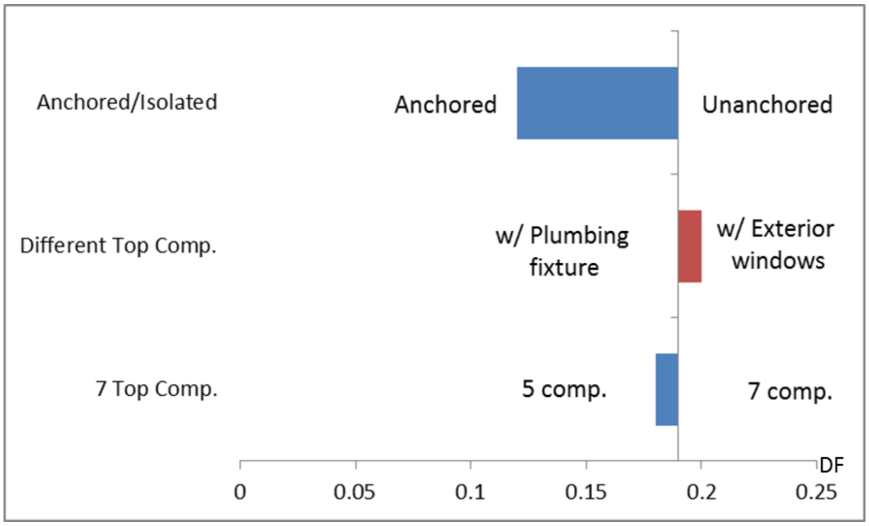


Figure 16. Sensitivity of Damage Factors of Non-structural components at Sa (1 sec, 5%) =1g

In the graph above, on the horizontal axis, the differences in value of damage factors are shown for each test. The base value of damage factors of the three tests are as follows.

Table 16. Base damage factors for the sensitivity test types

Test Type	Base DF
7 Top Comp.	0.18
Different Top Comp.	0.19
Anchored/Unanchored	0.12

Therefore, the results from the above three sensitivity tests prove that the installation status has a major effect on the final value of vulnerability functions. It causes a 58% difference in the result in this specific example.

5.7 UNCERTAINTY ANALYSIS:

There are uncertainties in the process of implementing the methodology. The uncertain parameters along with more descriptions of their effect in the process are discussed below.

There are possible uncertainties in measuring the quantities of nonstructural components in each story of a building. Also, since the methodology uses fragility curves and repair cost databases, there are uncertainties involved in the databases. In addition, there are uncertainties in selecting detailed nonstructural component types since sometimes the available databases are not an exact match to the detailed component type that one is looking for. The methodology categorizes buildings height into three groups of; lowrise, midrise and highrise. Therefore, there is uncertainty in categorizing the height of buildings. Also, since the methodology doesn't take into account buildings' vertical and plan irregularity, which can affect structural response and mode shape of buildings, there are uncertainties in the structural response because of not taking into account the irregularities. The methodology applies simplified structural analysis to determine structural response. Therefore, the simplified method can't capture the exact structural response of buildings and that brings uncertainty. There is uncertainty in results due to intensity measures, which are uncertain.

5.7.1 THREE CHOICES OF UNCERTAINTY ANALYSIS LEVEL

The uncertainty analysis can be performed in three different levels. The levels correspond to the amount of calculation effort and accuracy one wants to propagate. In the current work, only the first level of uncertainty analysis which is "one typical index building" is discussed and performed. The other two levels of uncertainty analysis are introduced briefly here but are discussed more in details in Cho and Porter (2013). The selection and combination of index buildings methodologies are fully described by Cho and Porter (2013). Briefly, there are three methods of selecting index buildings. As a brief description, the first method is using one index building, which is described in this work. The second method is selection of three index buildings to achieve poor, typical and superior construction qualities. The third methodology is selecting 7 index buildings which is not addressed in this work. The three methodologies are in accordance to the Global earthquake Model (GEM) work.

How many index buildings? If there is a time constraint the user can use a single index building that represents a typical case, as described in more detail shortly. With more time, one can explicitly propagate uncertainty. The user can select the characteristics and nonstructural inventory for three index buildings: one a poor case, with relatively fragile components, a typical case like the one just mentioned, and a superior case, with relatively rugged or seismically restrained components. Some judgment is required to establish the characteristics of these variants. Finally, with seven index buildings and some additional Monte Carlo simulation, one can explicitly propagate uncertainty associated within and between specimens.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The methodology presented here offers an analytical procedure for estimating the mean nonstructural seismic vulnerability of an index building, which can then be used to estimate the vulnerability of a building category. It requires one to select or design one or more index buildings to represent the category. The design is fairly schematic, requiring one to know the lateral force resisting system, height, floor area, the quantity of the top 5 or so nonstructural components that contribute most to the construction cost of the building, and the total nonstructural construction cost of the building. Each of these components is associated with a set of fragility functions (which relate the probability of a component of a particular type reaching or exceeding a particular damage state) and consequence functions (which quantify the cost to repair a particular component from a damage state specified by the fragility function). These come from ATC-58 or others sources. Story-level vulnerability is calculated as a sum of the vulnerability of each component, and the building-level vulnerability is derived as a function of ground motion by adding story-level vulnerability, accounting for mode shape, roof-level response, and normalizing by the fraction of nonstructural construction cost represented by the top 5 components.

The proposed methodology employs the same basic principles as the state-of-the-art methods specified in ATC-58, while reducing much of the effort. It draws on a substantial and growing body of fragility functions such as appear in the ATC-58 database, rigorously derived from laboratory tests or earthquake performance of fairly detailed building components. The consequence functions it uses are likewise drawn from the ATC-58 database or a variety of locally applicable repair-cost manuals and databases. At the same time, by focusing only on the top-5 nonstructural component categories, the analyst does not need to consider the fragility of all detailed non-structural components such as doorknob or wires. The structural analysis can be as sophisticated as ATC-58's multiple nonlinear dynamic analyses, or as simple as estimating roof acceleration and displacement using the N2 nonlinear pseudo-static structural analysis method, and applying one of three schematic mode shapes to interpolate story drifts and floor accelerations.

By using index buildings that are representative of a building class, one can avoid deriving vulnerability of every single building in the class using ATC-58 procedure. Running the ATC-58 on all buildings of the class is impossible or at least impractical. As a result, one can perform regional level seismic risk assessment by applying the methodology on different building classes in the region and add them all together to find the total loss due to damage of nonstructural components for any seismic excitation.

This thesis has not thoroughly addressed uncertainty propagation, although the broader project for the Global Earthquake Model has done so, by combining vulnerability functions for one, three, or seven individual index buildings. Each index building is analyzed along the lines presented here. Uncertainty is propagated mostly through the selection of index buildings and the method for combining results.

To run the present methodology, it is presumed that the analyst possesses at least a master's degree in structural engineering, but not much more. Also, the methodology takes two to four hours to assess an individual building, depending on the size and availability of the required data, to be applied and a result returned.

Since non-structural components make up more than half of a building's construction cost, those components need more consideration and it is advised to collect more information on damages and performance of non-structural components in future reconnaissance efforts and reports.

6.1 SUMMARY OF THE BENEFITS OF THE METHODOLOGY

The methodology is a simplified PBEE-2 methodology for nonstructural components in which it calculates mean repair cost loss for a particular index building for a range of shaking intensities. It offers a simplified structural analysis to derive structural response. Also, the methodology uses the already available fragility and repair cost data of ATC-58.

The methodology uses the principle of index building in which it categorizes buildings into a certain number of building models based on RSMeans construction cost manuals. The categorization is based on height, occupancy and lateral force resisting system. Therefore, by deriving vulnerability curves, it applies to all buildings that can be categorized in the building model and it accounts for differences between buildings in the class.

The methodology has the ability to account for uncertainties in a specific building.

The current methodology can rapidly estimate nonstructural vulnerability of a building class without full PBEE-2 effort.

The methodology appears to be practical for any building type defined by occupancy, structural system, and height. For the current work, three different example buildings were used and the results appear to be in reasonable agreement with other already available methods. The methodology is readily implemented in a spreadsheet.

As discussed in chapter 4, the current methodology picks the five top components and the sensitivity tests show that this is a reasonable number, generally representing half the nonstructural construction cost of the building. The methodology uses simplified structural analysis, which reduces problem setup and calculation time. The results of the methodology are comparable with other already available methods, and the current work has validated the result with those methods. The methodology is applicable worldwide.

6.2 LIMITATIONS OF THE METHODOLOGY

The methodology assumes that the most costly components contribute most to repair costs, and that they do so in proportion to their construction cost. It may be that some components omitted from the analysis may contribute disproportionately to loss. The hypothesis that vulnerability is insensitive to whether one uses the top 5, 6, 7, or 8 components in terms of construction cost have been tested, but have not been compared these results with an analysis that examines the building in complete detail, as one would with ATC-58. Therefore, it can be a subject of future research work.

The methodology uses simplified structural analysis and could potentially not account for some structural response such as soft story and requires further research.

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APPENDIX

A) Table 17. Top nonstructural components for different building types [RSMeans Square Foot Cost (2009)]

'RS Means Sq Ft Costs Manual	Type of Building	1	2	3	4	5	6	Total Construction cost	Const. cost per Sq. Ft ($)	% of total const. cost	Total non-strut. Const. cost ($)	% of total non-structural	NISTIR Classification					
M.010	Apartment 1-3 story	Plumbing fixtures	Exterior walls	Cooling generating	Energy supply	Light. & branch wiring			45.98	0.39	92.37	0.50	D2010	B2010	D3030	D3010	D5020	
M.020	Apartment 4-7 story	Plumbing fixtures	Exterior walls	Cooling generating	interior doors	Elevators & lifts			44.67	0.36	94.84	0.47	D2010	B2011.102	D3030	C1020	D1010	
M.030	Apartment 8-24 story	Exterior walls	Partitions	Elevators & lifts	Cooling generating	Light. & branch wiring		158.65	62.34	0.39	119.46	0.52	B2010	C1010	D1010	D3030	D5020	
M.120	College, classroom 2-3	Terminal & package units	Plumbing fixtures	Light. & branch wiring	Partitions	Interior Doors (Partitions)	Exterior Windows (Curtain walls)	126.72	$ 58.40	46%	$ 104.29	56%	D3050	D2010	D5020	C1010	C1020	B2020

Table 17(cont.) Top nonstructural components for different building types [RSMeans Square Foot Cost (2009)

NISTIR Classification						
	D4010	C3020	C3020		D3010	C3020
	D2010		D5020	D1010	D5020	B2020
	D3010	B2010	D1010	D5020	D2010	D5020
	D5020	D5020	D3050	D3030	B2010	B2010
	D3030	D3050	B2010	B2020	D3050	D3030
% of total non-struct. const. cost	0.44	0.58	0.58	0.65	0.57	0.55
Total non-structural		94.31	107.63	81.39	91.58	88.80
% of total const. cost	0.44	0.44	0.47	0.45	0.44	0.42
Construction cost per Sq. Ft ($)	33.76	55.12	62.29	52.52	52.34	49.22
Total Construction cost				115.61		
6						
5	Sprinklers	Floor finishes	Floor finishes	Communication & security	Energy supply	Floor finishes
4	Plumbing fixtures	Communication & security	Light. & branch wiring	Elevators & lifts	Light. & branch wiring	Exterior windows
3	Energy supply	Exterior walls	Elevators & lifts	Light. & branch wiring	Plumbing fixtures	Light. & branch wiring
2	Light. & branch wiring	Light. & branch wiring	Terminal & package units	Cooling generating	Exterior walls	Exterior walls
1	Cooling generating	Terminal & package units	Exterior walls	Exterior window	Terminal & package units	Cooling generating
Type of Building	Factory, 1 story	Office, 1 story	Office, 2-4 story	Office, 11-20 story	School, elementary	School, high, 2-3 story
'RS Means Sq Ft Costs Manual	M.200	M.455	M.460	M.480	M.560	M.570

A) Table 18. Survey on nonstructural probability of usage from home depot in Boulder

Nonstructural probability of usage survey			
Type:	Wall Partition, Type: Gypsum		
Total number of the type sold	611		
Selling time period	One week		
No.	Item description	Number sold	Probability of usage
1	1/2"x4'x8'	342	0.56
2	5/8"x4'x12'	5	0.01
3	1/2"x4'x8' (moisture resistant)	93	0.15
4	1/4"x4'x8'	30	0.05
5	5/8"x4'x8'	141	0.23

Table 19. Nonstructural probability of usage survey

Nonstructural probability of usage survey			
Type:	Wall Partition, Type: High End Marble or Wood Panel		
Total number of the type sold	445		
Selling time period	One week		
No.	Item description	Number sold	Probability of usage
1	7/16"x4'x8'	409	0.92
2	15/32"x4'x8'	36	0.08

Nonstructural probability of usage survey			
Type:	Lumber stud		
Total number of the type sold	611		
Selling time period	One week		
No.	Item description	Number sold	Probability of usage
1	2"x4"x8'	2548	0.93
2	2"x4"	179	0.065
3	2"x5/8"	9	0.003

B) Table 20. Regional nonstructural repair cost questionnaire for Shiraz building. Damage state descriptions.

No.	Component	Component description	DS1 description (slightly damaged)	DS2 description (moderately damaged)	DS3 description (severely damaged)
1	energy supply	water heater	The water heater internal connections are leaking	The electrical motor and the storage are damaged and should be repaired	The Electromotor is damaged and should be replaced
2	elevators & lifts	cable traction elevator	The fuses damaged, small electrical conflicts occurs	Small parts like electrical sensors or hydraulic jacks are damaged	The main board is damaged or the Electromotor is completely damaged and should be replaced
3	exterior walls	full length width hollow clay blocks with cement mortar and finishing	few shallow cracks on painting and finishing and needs to be repainted	few tiny but deep cracks through the partition depth but still repairable by new finishing and painting	several deep and wide cracks all over the wall and the whole partition needs to be demolished
4	partitions	half length hollow clay blocks with gypsum mortar and finishing	few shallow cracks on painting and finishing and needs to be repainted	few tiny but deep cracks through the partition depth but still repairable by new finishing and painting	several deep and wide cracks all over the wall and the whole partition needs to be demolished
5	interior doors	interior wooden door	The door frame is slightly moved outside and crackes are appeared on the supported walls	The door frame twisted and the hinges are damaged and needs to be replaced	The door and the frame is cracked and needs to completely replaced
6	cooling generating system	Water based cooler	The water pump is damaged	The cooler doors are damaged and the cooler box needs to be replaced	The cooler electro motor is damaged and electrical system of the cooler and the cooler box should be replaced

Table 21. Regional nonstructural repair cost questionare for shiraz building. Labor and material cost.

No.	Component	Component description	Labor hours DS1	Labor hours DS2	Labor hours DS3	Regional labor cost/hour (RC)	Material repair cost/unit (RC)	Material unit
1	energy supply	water heater	1	2	2	150000	5000000	one unit
2	elevators & lifts	cable traction elevator	0.5	1	3	100000	7500000	one unit
3	exterior walls	full length width hollow clay blocks with cement mortar and finishing	0.5	1	2	30000	2.00E+05	m^2
4	partitions	half length hollow clay blocks with gypsum mortar and finishing	0.2	0.5	1	30000	100000	meter
5	interior doors	interior wooden door	1	2	2	50000	3000000	one unit
6	cooling generating system	Water based cooler	0.5	1	1	100000	8000000	one unit

Table 22. Converted regional labor and material cost into U.S costs:

No.	Component	Repair Type	Labor hours DS1	Labor hours DS2	Labor hours DS3	Labor type	Labor coeff.	Material coeff.	Material repair cost/unit ($)	US labor/Iran labour (2012)	Iran labor cost/hour ($)	Iran labor cost DS1 ($)	Iran labor cost DS2 ($)	Iran labor cost DS3 ($)	Repair cost total DS1 ($)	Repair cost total DS2 ($)	Repair cost total DS3 ($)
1	Energy supply	Labor Dominant	1	2	2	Technical	0.8	0.2	416.667	2	12.5	12.5	25	25	93.333	103.333	103.3333
2	elevators & lifts	Labor Dominant	0.5	1	3	Technical	0.8	0.2	625	2	8.333	4.1667	8.333	25	128.333	131.667	145
3	exterior walls	Material/Labor	0.5	1	2	Non-technical	0.5	0.5	16.667	1	2.5	1.25	2.5	5	8.958	9.583	10.83333
4	Partitions	Material/Labor	0.2	0.5	1	Non-technical	0.5	0.5	8.333	1	2.5	0.5	1.25	2.5	4.41667	4.79167	5.416667
5	interior doors	Material/Labor	1	2	2	Non-technical	0.5	0.5	250	1	4.1667	4.1667	8.333	8.333	127.083	129.1667	129.1667
6	cooling generating system	Labor Dominant	0.5	1	1	Technical	0.8	0.2	666.667	2	8.333	4.1667	8.333	8.333	136.667	140	140

Table 23. Questionnaire parameters

US technical labor cost/hour ($)	40	
US non-tech labor cost/hour ($)	20	
	% of Labor	% of Material
Labor dominant:	80	20
Material dominant:	20	80
Labor dominant:	50	50
US labor/Iran labor (2012)	Technical:	1
US labor/Iran labor (2012)	Non-technical:	1
US labor/Iran labor (2012) 1 US $ / 1 Iran Rls (2012):	12000	