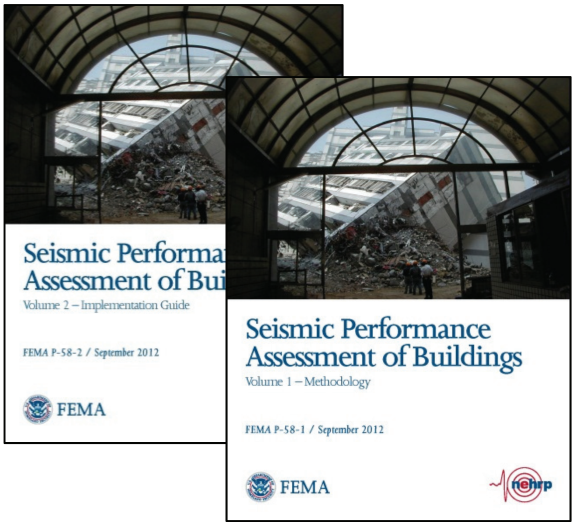

Background Document

FEMA P-58/BD-3.7.9

Taxonomy of Nonstructural Building Components

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Taxonomy of Nonstructural Building Components

Keith Porter

To model the seismic performance of nonstructural components, it is first necessary to define them. A categorization system (or taxonomy) of nonstructural components is developed. Nonstructural components are generally those that are fixed and do not contribute to structural strength or stiffness. Taxonomic groups are defined to meet ten objectives designed to ensure that meaningful fragility functions can be created for a group. The study focuses on those components and some contents that contribute significantly to earthquake-induced repair costs, casualties, or loss of use (dollars, deaths, or downtime). Standard or important proposed taxonomic systems are reviewed, in light of how well they meet the ten objectives. Important publications on component seismic fragility are reviewed. The existing system that comes closest to meeting the design objectives is then selected, modifications are proposed to make it meet the remaining, unsatisfied objectives, and the resulting taxonomic system detailed. An important novelty of this taxonomic system is that it attempts to distinguish common design or retrofit alternatives that make a difference in seismic performance, such as between braced versus unbraced piping, and between anchored versus unanchored electrical equipment. A taxonomic system that makes these distinctions can be used to assess the benefit of design or retrofit alternatives.

INTRODUCTION

NONSTRUCTURAL COMPONENTS IN PBEE

Several loss-estimation procedures have emerged since the 1970s that estimate earthquake repair costs by accumulating the costs to repair individual building components, or to replace the entire facility in case of collapse or excessive repair cost. Many of these methods share four analytical stages. In the first stage, called the hazard analysis, one or more levels of seismic excitation of interest are selected, and parameterized by an intensity measure such as PGA or S_a; often one or more ground-motion time-histories or response spectra are selected to correspond to the intensity measure. Structural analysis of one kind or another is then used to estimate component forces, deformations, and accelerations. In the third stage, referred to here as the damage analysis, one estimates component damage as a function of the member forces, energy demands, deformations, or accelerations to which the component is subjected during the earthquake. In the last stage, called here the loss analysis, one estimates each component's repair cost based on its damage state and the labor, materials, and other expenses that a construction contractor incurs to restore or replace the component. These costs are summed (using various refinements of cost-estimation procedures) to arrive at a total cost to repair the facility. Examples of loss-estimation methods that use such an approach include Czarnecki (1973), Kustu et al. (1982), and HAZUS (Kircher et al. 1997). Emerging methodologies include that of the Pacific Earthquake Engineering Research (PEER) Center (e.g., Porter 2003) and ATC-58 (e.g., Bachman 2004), for which the present study is performed. Figure 1 summarizes this methodology.

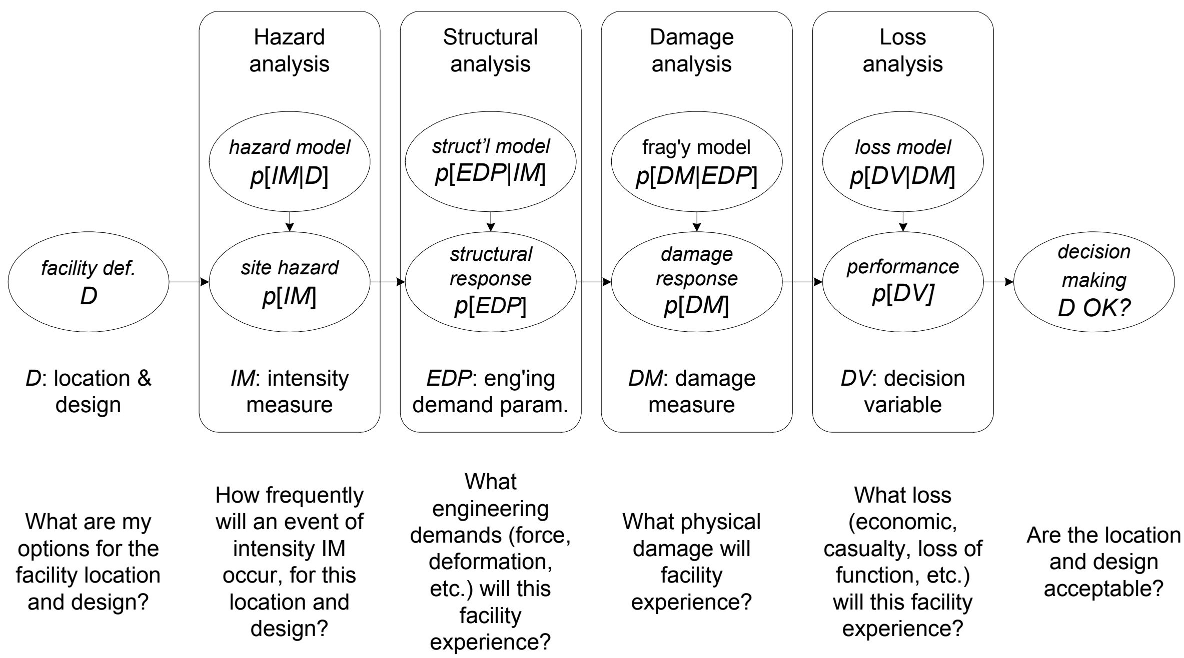

Figure 1. Generic PBEE methodology.

MEASURING THE EFFECTS DESIGN AND RETROFIT ALTERNATIVES

A PBEE methodology would be particularly useful to assess the benefit of a simple design change or mitigation effort. For example, the taxonomy should distinguish between future earthquake economic and human losses of a particular building with:

- Drywall partitions with screwed connections and metal studs and (a) fixed connection to the soffit above versus (b) sliding or flexible connection to the soffit above;
- Pendant light fixtures (a) with and (b) without seismic restraint;
- Freestanding cabinets (a) with and (b) without seismic restraint;

Each of these choices has an associated cost that is relatively easy to estimate. The challenge is quantifying the benefit, to determine whether the more-expensive alternative is justified. All three distinctions are believed to have a valuable effect on damage and loss. For example, the Federal government has allocated at least $48 million since 1994 to retrofit lights and ceilings in schools (FEMA 2004). Petal's (2004) epidemiological study of casualties in the 1999 Kocaeli (Turkey) earthquake showed that unanchored, freestanding cabinets caused 8,000 of the 80,000 casualties in that event. PBEE loss-estimation methods should be capable of detecting and measuring the performance difference produced by these risk-mitigation measures.

NEED FOR A NONSTRUCTURAL COMPONENT TAXONOMY

To measure the effects of design changes in nonstructural components, it is necessary first to define nonstructural components. To estimate the seismic performance of nonstructural components and to detect performance differences between common design alternatives requires a rigorous means of categorizing building components in sufficient detail that components with different damageability fall into different categories. For example, ceramic tile is far more fragile than vinyl tile, and caused substantial loss in the Van Nuys Holiday Inn in the 1971 San Fernando earthquake. Other examples that suggest a need for a nonstructural taxonomy include the different performance of full-height versus partial-height gypsum wallboard partitions, unbraced versus braced sprinkler piping, anchored and unanchored electrical equipment, etc. To lump together all varieties of tile finish, of interior partitions, or any of such diverse category of building component must produce large uncertainty in component fragility damageability, therefore large uncertainty in the system-level PBEE performance assessment. Estimates of future earthquake repair costs can be highly sensitive to uncertainty in component damageability (Porter et al. 2002).

To distinguish components with significantly different damageability helps design and retrofit decision-making. If one can estimate the performance of two competing designs, one can calculate the expected economic and life-safety benefits of choosing one over the other. One can address the question, for example, of whether it is cost effective to retrofit suspended ceilings and above-ceiling building-service equipment with seismic bracing, or in new construction, whether future savings justify the extra cost of using sliding connections t the top of interior wallboard partitions.

To make these distinctions and to estimate these performance differences in a design or retrofit situation, one needs a carefully designed categorization system of building components, and a set of fragility functions for each component category that is of interest in that design or retrofit situation.

Such a categorization system is referred to here as a taxonomy, in imitation of the taxonomy of organisms (Linneaus' richly branching system of kingdom, division, phylum, class, order, family, genus, and species). The present study examines taxonomies for nonstructural building components.

Do not confuse the definition of taxonomic groups and their PBEE attributes. The terms in which taxonomic groups are defined must be limited to characteristics that are typically shown in construction drawings and specifications, or are visible from inspecting the actual construction. The PBEE *attributes* of the class can include damageability, repair cost, repair duration, impact of component failure on operability or life safety, susceptibility to water damage, inflammability, etc. These attributes are important, and can be assigned to each taxonomic group after the group is defined, but they cannot be *part* of its definition, if the taxonomy is to be useful to earthquake engineers.

For example, imagine a suspended ceiling of given dimensions, grid system, tile materials, wall capture conditions, strut and wire-brace restraint conditions, and other conditions such as light fixtures resting on the grid. Some combination of these characteristics define the taxonomic group to which that ceiling belongs. An engineer performing an PBEE analysis to estimate future earthquake repair cost, repair duration, and casualties should be able to determine the taxonomic group of the ceiling being analyzed, without *already knowing* its attributes, in terms of damageability, etc. To perform the analysis, the engineer will have to be able to look up or derive these attributes somehow, e.g., from an online, interactive database.

Flexible but not dynamic taxonomy. The taxonomy to be proposed here should not be static, and should allow for the easy addition or modification of groups as future testing or other developments dictate. However, the taxonomy need not be highly dynamic either, restructured with every new query. A slowly developing taxonomic system does not prevent one from dynamically grouping components in different, meaningful ways. For example, in both the Linnaean system and in existing taxonomies of building components, groups are occasionally added, renamed, and removed, without necessitating a complete restructuring of the taxonomic system[1]. One can list species of organism that breath air or that eat meat without restructuring the Linnaean taxonomic system, by performing a query on a database. Similarly, one should be able to list the building components whose engineering demand parameter is peak transient drift by performing a database query that contains attributes for each taxonomic group, without dynamically restructuring the taxonomy.

SCOPE, OBJECTIVES AND METHODOLOGY

SCOPE

The present study examines nonstructural components of commercial and engineered residential buildings. The definition of "nonstructural" depends on the results of the study, but in general it refers here to common fixed components that would typically be built as part of the initial construction and do not contribute substantially to structural strength or stiffness. The scope is further limited to components that typically contribute significantly to post-earthquake repair costs, earthquake-induced casualties, and loss of use (dollars, deaths, and downtime). To a limited extent, non-fixed contents are considered, because contents matter to downtime and casualties. Insofar as occupancy matters to the taxonomy, the following occupancies are within the scope of ATC-58 and therefore this project: RES3, RES4, RES5, COM1, COM4, COM5, COM6, COM7, GOV1, GOV2, EDU1, and EDU2. Possibly within scope are RES6 and COM2. These occupancy codes refer to the HAZUS99-SR2 Technical Manual Table 3.2 (NIBS and FEMA 1999).

OBJECTIVES

A nonstructural component taxonomy for earthquake engineering purposes could be designed to facilitate either the damage analysis (estimation of physical damage as a function of structural

[1] Revolutions do occur in both domains. There is controversy about how organisms should be classified, whether entirely by branching order or by a combination of branching order and physical and environmental similarity. Similarly, both the UNIFORMAT and MasterFormat systems, described later, are undergoing radical change. Revolutions in both domains occur periodically, allowing for new knowledge, but not on a day-to-day, user-to-user basis. Yet they all still work.

response and design), loss analysis (repair cost, casualties, or repair duration, as a function of damage and design), or both. The focus of the present study is on damageability, although some consideration is given to loss. Important features of such a taxonomy include:

1. *Clear definitions*. Two people examining the same nonstructural component should independently assign the same taxonomic group based solely on the text definition of the taxonomic group. One must not need to know about a component's fragility functions in order to assign it to a taxonomic group.

2. *Common fragility functions.* This means three things: (i) All members of the taxonomic group share a common set of damage states relevant to the facility's seismic performance. (ii) All members are sensitive to the same type of excitation (force, deformation, acceleration, etc.). (iii) The excitation at which members enter a particular damage state is identically distributed. The cumulative distribution functions of these capacities are referred to a fragility functions.

3. *Distinguishes differences in seismic performance.* That is, the taxonomy distinguishes supposed earthquake-resistant versions of a component from a non-earthquake resistant version, such as between the "before" and "after" states of common seismic retrofits. For example, if bracing sprinkler piping is believed significantly to reduce damageability, then braced and unbraced piping systems should fall into different taxonomic groups. This is a somewhat more restrictive requirement than "common fragility functions." One can create a fragility function for all varieties of some component without differentiating between varieties that matter to seismic performance. The fragility function for the undifferentiated category will simply have greater uncertainty, and will not enable the analyst to assess the benefit of a change within that category.

4. *Testable*. The taxonomic group is homogenous enough that one can with reasonable confidence perform a set of laboratory tests, analyses, or expert-opinion surveys to establish a single set of fragility functions for the entire group within the constraints of common a research budget (e.g., a single doctoral dissertation).

5. *Amenable to assessment of consequences*. For example, taxons can be rated in some way (e.g., high, medium, or low) for contribution to historic losses, so as to focus fragility testing efforts. They can be rated in some way (e.g., yes or no) for inflammability, subject to water damage, potential to cause injury, etc., so as to direct subsequent loss assessment.

6. *Flexible.* The taxonomic system should not presuppose future findings of fragility, and it should allow for future addition of taxonomic groups, as new experimental investigations dictate, and as new materials and systems are developed. For example, it may be found through experimentation that some existing taxonomic group should be subdivided into new groups, because the new groups have less uncertainty on damageability or other PBEE attributes. A taxonomy will be judged to be flexible if both (a) it explicitly leaves room for the addition of taxonomic groups, and (b) a mechanism currently exists to do so, such as through an interactive database or a group that maintains and periodically updates the taxonomy. It will be judged to be somewhat flexible if it satisfies only one of these two conditions.

7. *Collectively exhaustive*. The taxonomy should be collectively exhaustive, insofar as any building component can be assigned to a taxonomic group. The taxonomy need not be mutually exclusive. Considering the example cited above for a flexible taxonomy, it will be desirable to have available both older or larger groups and newer or finer groups for purposes of comparing or refining analyses.

8. *Simple*. The taxonomy has as few groups as possible, while still meeting the other requirements. It is problematic to define what is simple, but for present purposes, a taxonomy will be judged simple if it contains fewer than 100 groups, somewhat simple if it both contains between 100 and 1,000 groups and those groups are arranged hierarchically so that one could find a desired group without being familiar with the entire taxonomy.

9. *Collapsible.* It is desirable to be able to define common combinations and relative quantities of nonstructural components so that fragility or vulnerability functions could be created by aggregating the fragilities or vulnerabilities of detailed components, while still distinguishing design or retrofit alternatives. For example, it would be desirable to create one vulnerability function for drift-sensitive nonstructural components of current-code-compliant class-A office buildings that meet a set of observable seismic resistance criteria. A taxonomy will be judged to be collapsible if taxonomic groups can be combined and the resulting combinations still distinguish differences in seismic performance.

10. *Familiar to construction contractors and engineering practitioners*. It is desirable, though not necessary, that engineers and construction contractors be familiar with the taxonomic system, to facilitate communication and, particularly, for repair-cost estimation. If the new

taxonomic system for PBEE corresponds readily to an existing taxonomic system, it can give PBEE engineers access to cost data, historical databases, and tools for construction scheduling. Employing or elaborating an existing taxonomic system will also help simplify the maintenance and further development of the taxonomic system.

METHODOLOGY

The taxonomy is developed first by reviewing the desired features, in consultation with an oversight committee of scholars and practitioners familiar with the objectives and principles of performance-based earthquake engineering. Next, existing taxonomic systems are reviewed, to see how well each satisfies the objectives listed above. Relevant damage data are reviewed, including publications on fragility testing and observed empirical seismic performance, to identify types of nonstructural components that contribute significantly to earthquake losses, and to identify design alternatives that make a material difference to seismic performance and might therefore impact the design of the taxonomy.

It is anticipated that no existing, accepted taxonomy satisfies all the objectives. The existing taxonomy that in some way comes closest to satisfying the objectives is then identified, and modifications are proposed to meet the remaining objectives. A sample of the resulting taxonomic system is then created. The proposed system and the sample are then presented to the oversight committee for review. That is the stage of the present draft of this study. In the final draft, after review and commentary by the oversight committee, a final taxonomic system will be proposed.

Approach to identify important components. The Kao et al. (1999) database of historic nonstructural damage will be analyzed to identify the types of nonstructural components that most frequently appear in the damage reports, and by inference, that most frequently contribute to actual damage. The database does not have a standard naming system for types of nonstructural components; more than 1200 names are used in the database, with many nearly identical names (e.g., pipe, pipes, piping, pipework, etc.). The first step will be to standardize the naming of apparently dominant system (e.g., pipe, ceiling, lights). The next will be to identify either (a) the systems that contribute 90% of recorded damage incidents or (b) the 5 to 10 systems that have the largest number of recorded damage incidents, whichever is less. These systems and the components that comprise them will be considered important for present purposes. The final taxonomy will provide detail about components in these important systems;

less attention will be paid to other, less-important systems. (The word "system" is used here loosely; the final definition will depend on the final taxonomy.)

Approach to aggregation. It is desirable that the taxonomy include at least one formal level of aggregation (systems). Examples are HVAC, architectural partitions, exterior glazing, or automatic sprinklers. A higher level of aggregation might also be valuable, perhaps referred to as a supersystem or level-2 system. Examples might be drift-sensitive nonstructural and acceleration-sensitive nonstructural components, per HAZUS. The system, supersystem, etc., to which each component in the taxonomy belongs will be attributes of the taxonomy. For example, unanchored low-voltage switchgear could belong to the electrical-distribution system, and to the acceleration-sensitive nonstructural supersystem.

It would be valuable to define samples of such systems and supersystems, with at least two versions of each system or supersystem, with the versions representing design alternatives. The purpose would be to facilitate development of a set of system and supersystem fragility and vulnerability functions. For example, two or more electrical-system fragility functions could be developed, one representing unanchored and unbraced conditions, the other, anchored and braced. One such fragility function could represent the probability of electrical-system operational failure as a function of spectral acceleration response. A vulnerability function might be the cost or time to restore the electrical system, as a function of spectral acceleration. It might be necessary to condition the fragility functions and vulnerability functions on characteristics of the building in which the system is housed, such as building dimensions, structural period, occupancy, etc.

The design of such sample systems or supersystems is not part of this work, nor is the development of their fragility or vulnerability functions, but the present work will be performed anticipating that such work might be performed later.

LITERATURE REVIEW

With the objectives and methodology stated, a review of relevant literature is now presented. Three general categories of prior work are examined: taxonomies designed for use in earthquake engineering; general building component taxonomies; and a brief review of literature on component damageability, because of its relevance to selecting or designing a taxonomy.

EXISTING TAXONOMIES DESIGNED FOR EARTHQUAKE ENGINEERING

International Code Council (2000); ASCE 7-05 (ASCE 2005). The International Building Code and ASCE's Minimum Design Loads for Buildings and Other Structures both contain (in a way) a taxonomy of nonstructural components. Table 1 contains parameters of these two documents' seismic design requirements for architectural components. Table 2 shows a similar taxonomy for mechanical and electrical components. Because it comes from a building code, the taxonomy is familiar to engineers, although perhaps not to construction contractors because of its location in a chapter dedicated to structural design. It is short and simple. However, its disadvantages for present purposes are numerous. The definitions are qualitative, somewhat vaguely defined, and do not appear to be collectively exhaustive. For example, what is the meaning of limited-deformability veneer, how is it distinguished from low-deformability veneer, and is there no such thing as moderate or high-deformability veneer? These categories would be circularly defined if used in a taxonomy for damage analysis. The groups are too large to share common functions, to be testable, to be amenable to the assessment of consequences, or to distinguish seismic performance of similar components installed differently, as with braced versus unbraced sprinkler pipe.

Table 1. Architectural component categories in the IBC and ASCE 7 (ICC 2000 and ASCE 2005)

Architectural Component or Element	a_p [a]	R_p [b]
Interior Nonstructural Walls and Partitions [b]		
Plain (unreinforced) masonry walls	1.0	1.5
All other walls and partitions	1.0	2.5
Cantilever Elements (Unbraced or braced to structural frame below its center of mass)		
Parapets and cantilever interior nonstructural walls	2.5	2.5
Chimneys and stacks where laterally braced or supported by the structural frame	2.5	2.5
Cantilever Elements (Braced to structural frame above its center of mass)		
Parapets	1.0	2.5
Chimneys and Stacks	1.0	2.5
Exterior Nonstructural Walls [b]	1.0[b]	2.5
Exterior Nonstructural Wall Elements and Connections [b]		
Wall Element	1.0	2.5
Body of wall panel connections	1.0	2.5
Fasteners of the connecting system	1.25	1.0
Veneer		
Limited deformability elements and attachments	1.0	2.5
Low deformability elements and attachments	1.0	1.5
Penthouses (except where framed by an extension of the building frame)	2.5	3.5
Ceilings		
All	1.0	2.5
Cabinets		
Storage cabinets and laboratory equipment	1.0	2.5
Access Floors		
Special access floors (designed in accordance with Section13.5.7.2)	1.0	2.5
All other	1.0	1.5
Appendages and Ornamentations	2.5	2.5
Signs and Billboards	2.5	2.5
Other Rigid Components		
High deformability elements and attachments	1.0	3.5
Limited deformability elements and attachments	1.0	2.5
Low deformability materials and attachments	1.0	1.5
Other Flexible Components		
High deformability elements and attachments	2.5	3.5
Limited deformability elements and attachments	2.5	2.5
Low deformability materials and attachments	2.5	1.5

[a] A lower value for a_p shall not be used unless justified by detailed dynamic analysis. The value for a_p shall not be less than 1.00. The value of a_p = 1 is for rigid components and rigidly attached components. The value of a_p = 2.5 is for flexible components and flexibly attached components. See Section 11.2 for definitions of rigid and flexible.

[b] Where flexible diaphragms provide lateral support for concrete or masonry walls and partitions, the design forces for anchorage to the diaphragm shall be as specified in Section 12.11.2.

Table 2. Mechanical and electrical component categories in the IBC and ASCE 7 (ICC 2000 and ASCE 2005)

Mechanical and Electrical Components	a_p[a]	R_p
Air-side HVAC, fans, air handlers, air conditioning units, cabinet heaters, air distribution boxes, and other mechanical components constructed of sheet metal framing.	2.5	3.0
Wet-side HVAC, boilers, furnaces, atmospheric tanks and bins, chillers, water heaters, heat exchangers, evaporators, air separators, manufacturing or process equipment, and other mechanical components constructed of high deformability materials.	1.0	2.5
Engines, turbines, pumps, compressors, and pressure vessels not supported on skirts and not within the scope of Section 15.	1.0	2.5
Skirt-supported pressure vessels not within the scope of Section15.	2.5	2.5
Elevator and escalator components.	1.0	2.5
Generators, batteries, inverters, motors, transformers, and other electrical components constructed of high deformability materials.	1.0	2.5
Motor control centers, panel boards, switch gear, instrumentation cabinets, and other components constructed of sheet metal framing.	2.5	3.0
Communication equipment, computers, instrumentation and controls.	1.0	2.5
Roof mounted chimneys, stacks, cooling and electrical towers laterally braced below their center of mass.	2.5	3.0
Roof mounted chimneys, stacks, cooling and electrical towers laterally braced above their center of mass.	1.0	2.5
Lighting fixtures.	1.0	1.5
Other mechanical or electrical components.	1.0	1.5
Vibration Isolated Components and Systems [b]		
Components and systems isolated using neoprene elements and neoprene isolated floors with built-in or separate elastomeric snubbing devices or resilient perimeter stops.	2.5	2.5
Spring isolated components and systems and vibration isolated floors closely restrained using built-in or separate elastomeric snubbing devices or resilient perimeter stops.	2.5	2.0
Internally isolated components and systems.	2.5	2.0
Suspended vibration isolated equipment including in-line duct devices and suspended internally isolated components.	2.5	2.5
Distribution Systems		
Piping in accordance with ASME B31, including in-line components with joints made by welding or brazing.	2.5	12.0
Piping in accordance with ASME B31, including in-line components, constructed of high or limited deformability materials, with joints made by threading, bonding, compression couplings, or grooved couplings.	2.5	6.0
Piping and tubing not in accordance with ASME B31, including in-line components, constructed of high deformability materials, with joints made by welding or brazing.	2.5	9.0
Piping and tubing not in accordance with ASME B31, including in-line components, constructed of high or limited deformability materials, with joints made by threading, bonding, compression couplings, or grooved couplings.	2.5	4.5
Piping and tubing constructed of low deformability materials, such as cast iron, glass, and nonductile plastics.	2.5	3.0
Ductwork, including in-line components, constructed of high deformability materials, with joints made by welding or brazing.	2.5	9.0
Ductwork, including in-line components, constructed of high or limited deformability materials with joints made by means other than welding or brazing.	2.5	6.0
Ductwork, including in-line components, constructed of low deformability materials, such as cast iron, glass, and nonductile plastics.	2.5	3.0
Electrical conduit, bus ducts, rigidly mounted cable trays, and plumbing.	1.0	2.5
Manufacturing or process conveyors (nonpersonnel).	2.5	3.0
Suspended cable trays.	2.5	6.0

[a] A lower value for a_p is permitted where justified by detailed dynamic analyses. The value for a_p shall not be less than 1.0. The value of a_p equal to 1.0 is for rigid components and rigidly attached components. The value of a_p equal to 2.5 is for flexible components and flexibly attached components.

[b] Components mounted on vibration isolators shall have a bumper restraint or snubber in each horizontal direction. The design force shall be taken as $2F_p$ if the nominal clearance (air gap) between the equipment support frame and restraint is greater than 1/4 in. If the nominal clearance specified on the construction documents is not greater than 1/4 in., the design force is permitted to be taken as F_p.

HAZUS (NIBS and FEMA 1999). HAZUS is a FEMA-sponsored standard, nationally applicable software methodology for assessing earthquake risk. Subsequent versions of the software added the ability to assess risk from hurricanes and floods. In the process of developing its loss-estimation algorithm, HAZUS' developers created a taxonomy of common nonstructural components and contents of buildings, shown below in Table 3. It is simple and amenable to the assessment of consequences (that being its purpose). It has important deficiencies for present purposes. The groups border on being too large to be testable. It is not intended to reflect differences in seismic performance between common design or retrofit alternatives. For example, it does not distinguish between restrained and unrestrained freestanding cabinets (relevant, as noted earlier, to injury epidemiology) or between anchored and unanchored electrical equipment (relevant to repair costs, repair duration, and post-earthquake operability). Some important components are missing: note the absence of suspended ceilings and glazing from the taxonomy.

Table 3. HAZUS 99 taxonomy of building nonstructural components and contents

Type	Item	Drift-Sensitive*	Acceleration-Sensitive*
Architectural	Nonbearing Walls/Partitions	•	○
	Cantilever Elements and Parapets		•
	Exterior Wall Panels	•	○
	Veneer and Finishes	•	○
	Penthouses	•	
	Racks and Cabinets		•
	Access Floors		•
	Appendages and Ornaments		•
Mechanical and Electrical	General Mechanical (boilers, etc.)		•
	Manufacturing and Process Machinery		•
	Piping Systems	○	•
	Storage Tanks and Spheres		•
	HVAC Systems (chillers, ductwork, etc.)	○	•
	Elevators	○	•
	Trussed Towers		•
	General Electrical (switchgear, ducts, etc.)	○	•
	Lighting Fixtures		•
Contents	File Cabinets, Bookcases, etc.		•
	Office Equipment and Furnishings		•
	Computer/Communication Equipment		•
	Nonpermanent Manufacturing Equipment		•
	Manufacturing/Storage Inventory		•
	Art and other Valuable Objects		•

* Solid dots indicate primary cause of damage, open dots indicate secondary cause of damage

Porter (2000). The current author presented a component taxonomy designed for performance-based earthquake engineering. It is based on the RS Means Assembly numbering system (described later), extended with a "condition" attribute added to each RS Means category, to account for differences in installation or other characteristics that matter to seismic performance. For example, the taxonomy distinguishes between braced and unbraced sprinkler piping, anchored and unanchored generators, etc. It includes a judgment of the relevant engineering demand parameter (the seismic excitation most likely to cause damage). It lists categories of common, potentially damageable components in nine UNIFORMAT divisions. Since it is based on UNIFORMAT and RS Means, the taxonomy offers clear, familiar definitions and ready application of published databases of cost and repair duration, useful in assessing consequences. (For a small, illustrative subset of the taxonomy, fragility functions, repair costs, and repair durations are tabulated; these have been supplemented in Porter et al. 2002 and Beck et al. 2002. Eighty-three fragility functions and repair-cost distributions for common components are currently available.) The categories are small enough to be tested. The provision of the condition attribute allows for taxons to be small enough to have common fragility functions and to distinguish seismic performance. Its categories are not collectively exhaustive; no components in Divisions 10 (special construction) and higher are included. Furthermore, many higher-level aggregations of categories are not broken out into fine detail. For example, exterior glazing is not differentiated by pane size or gap size, nor are interior wallboard partitions differentiated between full-height, partial-height, etc. Since it is an extension of the RS Means assembly-numbering system, a complete listing would be very large, and its use for present purposes would potentially raise concerns about copyrights and costs of manuals.

Taghavi and Miranda (2003). These authors describe a Microsoft Access database of the seismic performance of nonstructural components of commercial buildings. The database includes a taxonomy of components, as well as example photographs and attributes of fragility, repair cost, repair actions, and damage consequences in terms of building functionality and life-safety threat. The taxonomic groups are identical to those of RS Means assemblies (Miranda, 2005). As it relies on the RS Means categories, the taxonomy uses familiar, clear terms, with categories small enough to be tested within a single doctoral dissertation. However, for the same reason, the complete listing would be very large, and its use for present purposes would potentially raise concerns about copyrights and costs of manuals. As with RS Means assembly-numbering system, the taxonomy does not distinguish seismic performance features. For example, no distinction is made between braced and unbraced suspended ceilings, between braced and unbraced automatic sprinklers, and between mechanical and electrical equipment with and without seismic restraint.

Antaki (2004) offers a conceptual taxonomy of all fixed facilities by expanding on a scheme developed by the Electric Power Research Institute as part of the Seismic Qualification of Utilities Guidelines (SQUG). The SQUG guidelines are used to determine whether electrical and mechanical equipment in energy facilities are adequately seismically resistant. They use checklists first to identify equipment within a category and then to assess the features of the equipment to determine seismic adequacy. SQUG's Generic Implementation Procedure (GIP) documents this methodology. It comprises a book and 50 or so manuals, and has been republished as US Department of Energy guide DOE-EH-0545. Antaki proposes an expansion of this procedure to address all fixed facilities. His taxonomy has four levels: (i) categories are defined in terms of the discipline of the engineers who design the system; (ii) classes and (iii) groups defined per the SQUG inclusion system; and (iv) attributes that are believed largely to be determine whether the component is seismically resistant: material; design compliant with national standards for normal operation; quality of fabrication; effects of operation on seismic resistance; and effects of maintenance on seismic resistance. Figure 2 partially illustrates this taxonomic system. Its tree-like structure allows the taxonomy to be collapsed. The framework omits architectural elements, so cannot be said to be collectively exhaustive. To the extent that it is developed, some of the components are vaguely defined, e.g., under static mechanical components, what is "equipment" if it is distinct from "boilers?" Groups appear to be too large to be testable or readily amenable to the assessment of consequences. For example, "frames" in the structural-element class: how would one test these or assess their repair cost or repair duration as a single, monolithic group? Because the taxonomy has been developed to some extent by and for a specialty within electrical and mechanical engineering, some of the definitions would be unfamiliar to earthquake engineers.

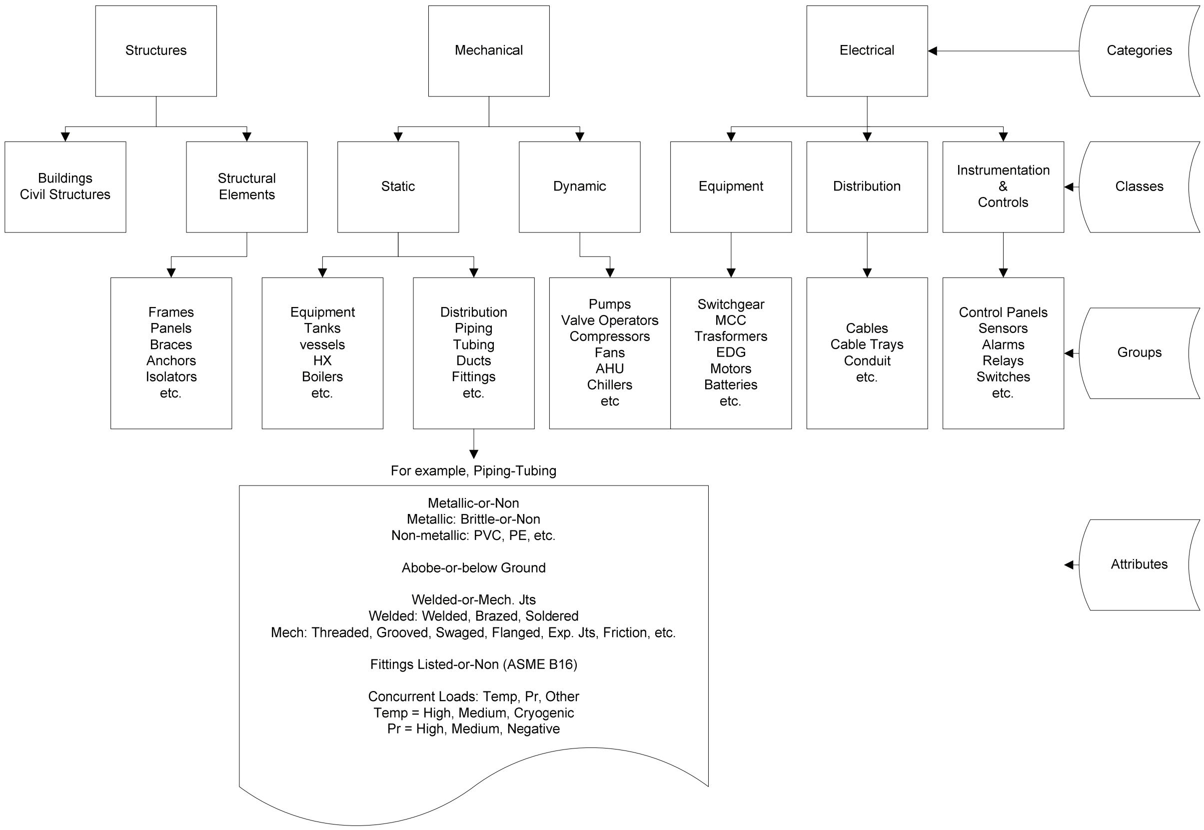

Figure 2. A conceptual taxonomy of all fixed facilities (Antaki 2004)

GENERAL BUILDING-COMPONENT TAXONOMIES

UNIFORMAT-II. The Construction Specification Institute (CSI) has produced a taxonomic system for building components, the current version of which is called UNIFORMAT-II (ASTM 2002). Figure 3 summarizes its framework for categorizing the built environment; only the shaded blocks (construction, buildings, and sitework) are relevant here. Table 4 summarizes the UNIFORMAT-II classification of building elements. UNIFORMAT-II includes three levels of increasing detail, in a branching structure: Level 1—Major Group Elements, Level 2—Group Elements, and Level 3—Individual Elements. Every Level-1 taxonomic group includes one or more Level-2 taxonomic groups that belong only to that Level-1 taxonomic group. Similarly, every Level-2 taxonomic group includes one or more Level-3 groups that belong only to that Level-2 group. For example, within the Level-1 group Shells is a Level-2 group called Exterior Closure. Within Exterior Closure is a Level-3 group called Exterior Windows.

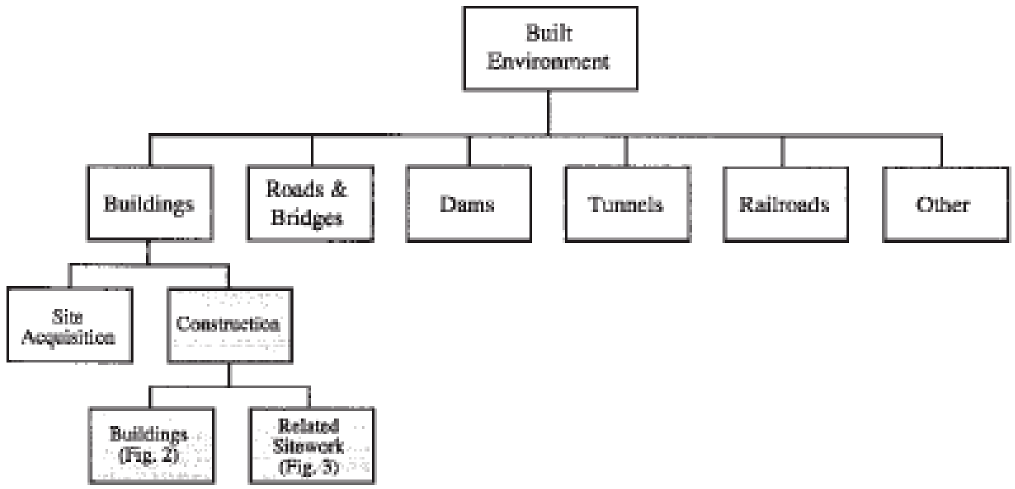

Figure 3. UNIFORMAT-II framework of the built environment. Only construction and buildings are relevant here.

Table 4. UNIFORMAT-II classification of building elements.

Level 1 Major Group Elements	Level 2 Group Elements	Level 3 Individual Elements
A SUBSTRUCTURE	A10 Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade
	A20 Basement Construction	A2010 Basement Excavation A2020 Basement Walls
B SHELL	B10 Super Structure	B1010 Floor Construction B1020 Roof Construction
	B20 Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors
	B30 Roofing	B3010 Roof Coverings B3020 Roof Openings
C INTERIORS	C10 Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings
	C20 Stairs	C2010 Stair Construction C2020 Stair Finishes
	C30 Interior Finishes	C3010 Wall Finishes C3020 Floor Finishes C3030 Ceiling Finishes
D SERVICES	D10 Conveying	D1010 Elevators & Lifts D1020 Escalators & Moving Walks D1090 Other Conveying Systems
	D20 Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rain Water Drainage D2090 Other Plumbing Systems
	D30 HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment
	D40 Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems
	D50 Electrical	D5010 Electrical Service & Distribution D5020 Lighting and Branch Wiring D5030 Communications & Security D5090 Other Electrical Systems
E EQUIPMENT & FURNISHINGS	E10 Equipment	E1010 Commercial Equipment E1020 Institutional Equipment E1030 Vehicular Equipment E1090 Other Equipment
	E20 Furnishings	E2010 Fixed Furnishings E2020 Movable Furnishings
F SPECIAL CONSTRUCTION & DEMOLITION	F10 Special Construction	F1010 Special Structures F1020 Integrated Construction F1030 Special Construction Systems F1040 Special Facilities F1050 Special Controls and Instrumentation
	F20 Selective Building Demolition	F2010 Building Elements Demolition F2020 Hazardous Component Abatement

The advantages of UNIFORMAT-II for present purposes are that it is already well defined, the construction industry is familiar with and accepts it, and the American Society of Testing and Materials will continue to maintain it for some time. Its groups are collectively exhaustive and small in number: only 55 groups, and a listing occupies only one page. Its disadvantages are numerous, however. The groups are not quite clearly defined: it is unclear, for example, whether the interior finish to exterior walls belongs to B2010 (Exterior Walls) or C3010 (Wall Finishes). The groups are too large reasonably to share common fragility functions or to be testable. They do not distinguish differences in seismic performance. For example, D4010, Sprinklers, has no subcategories to distinguish braced sprinkler pipes from unbraced. There is no distinction between exterior walls of precast concrete, stucco, timber, or gypsum wallboard. The overly large grouping prevents the taxonomic system from facilitating cost estimation or repair scheduling, as the groups are too large to associate historical databases or manuals of repair costs.

NISTIR 6389. NIST (1999) proposed a revision to UNIFORMAT-II to include a fourth level of definition to augment the three levels in the 1997 standard. The additional level of detail, for example, distinguishes fixed partitions (C1011 in the proposed numbering system) from site-built compartment cubicles (C1015) and windows (B2021) from curtain walls (B2022). Because it is an extension of UNIFORMAT-II, it is collectively exhaustive and would be familiar to construction contractors and engineering practitioners. The revision makes the taxonomy more clearly defined, e.g., eliminating the ambiguity about the group to which interior finishes on exterior walls belongs[2]. The groups are smaller and more testable than in UNIFORMAT-II, and more amenable to the assessment of consequences. A complete listing takes only three pages (see Table 5), and contains 274 categories. Nonetheless, the authors particularly note the point that with the greater level of detail comes readier access to existing cost data, stronger validation of new cost estimates against the costs of similar past construction, and easier construction scheduling. However, there are limitations to the revision for present purposes: even with the additional level of detail, the revision does not distinguish differences in seismic performance. For example, there is no distinction between braced and unbraced sprinkler piping or between precast concrete, stucco, wood, and gypsum wallboard exterior walls.

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[2] Some additions or clarifications would be desirable to make the taxonomy useful for PBEE, especially the addition of separate categories for structural elements of the gravity and lateral-force-resisting systems.

Table 5. NISTIR 6389 proposed level 4 for the UNIFORMAT-II Classification of Buildings

Level 3 Elements	Level 4 Sub-Elements
A1010 Standard Foundations	A1011 Wall Foundations A1012 Column Foundations & Pile Caps A1013 Perimeter Drainage & Insulation
A1020 Special Foundations	A1021 Pile Foundations A1022 Grade Beams A1023 Caissons A1024 Underprinting A1025 Dewatering A1026 Raft Foundations A1027 Pressure Injected Grouting A1029 Other Special Conditions
A1030 Slab on Grade	A1031 Standard Slab on Grade A1032 Structural Slab on Grade A1033 Inclined Slab on Grade A1034 Trenches, Pits & Bases A1035 Under-Slab Drainage & Insulation
A2010 Basement Excavation	A2011 Excavation for Basements A2012 Structure Back Fill & Compaction A2013 Shoring
A2020 Basement Walls	A2021 Basement Wall Construction A2022 Moisture Protection A2023 Basement Wall Insulation A2024 Interior Skin
B1010 Floor Construction	B1011 Suspended Basement Floors Construction B1012 Upper Floors Construction B1013 Balcony Floors Construction B1014 Ramps B1015 Exterior Stairs and Fire Escapes B1016 Floor Raceway Systems B1019 Other Floor Construction
B1020 Roof Construction	B1021 Flat Roof Construction B1022 Pitched Roof Construction B1023 Canopies B1029 Other Roof Systems
B2010 Exterior Walls	B2011 Exterior Wall Construction B2012 Parapets B2013 Exterior Louvers, Screens, and Fencing B2014 Exterior Sun Control Devices B2015 Balcony Walls & Handrails B2016 Exterior Soffits

Level 3 Elements	Level 4 Sub-Elements
B2020 Exterior Windows	B2021 Windows B2022 Curtain Walls B2023 Storefronts
B2030 Exterior Doors	B2031 Glazed Doors & Entrances B2032 Solid Exterior Doors B2033 Revolving Doors B2034 Overhead Doors B2039 Other Doors & Entrances
B3010 Roof Coverings	B3011 Roof Finishes B3012 Traffic Toppings & Paving Membranes B3013 Roof Insulation & Fill B3014 Flashings & Trim B3015 Roof Eaves and Soffits B3016 Gutters and Downspouts
B3020 Roof Openings	B3021 Glazed Roof Openings B3022 Roof Hatches B3023 Gravity Roof Ventilators
C1010 Partitions	C1011 Fixed Partitions C1012 Demountable Partitions C1013 Retractable Partitions C1014 Site Built Toilet Partitions C1015 Site Built Compartments Cubicles C1016 Interior Balustrades and Screens C1017 Interior Windows & Storefronts
C1020 Interior Doors	C1021 Interior Doors C1022 Interior Door Frames C1023 Interior Door Hardware C1024 Interior Door Wall Opening Elements C1025 Interior Door Sidelights & Transoms C1026 Interior Hatches & Access Doors C1027 Door Painting & Decoration
C1030 Fittings	C1031 Fabricated Toilet Partitions C1032 Fabricated Compartments & Cubicles C1033 Storage Shelving and Lockers C1034 Ornamental Metals and Handrails C1035 Identifying Devices C1036 Closet Specialties C1037 General Fittings & Misc. Metals
C2010 Stair Construction	C2011 Regular Stairs C2012 Curved Stairs C2013 Spiral Stairs C2014 Stair Handrails and Balustrades
C2020 Stair Finishes	C2021 Stair, Tread, and Landing Finishes C2022 Stair Soffit Finishes C2023 Stair Handrail & Balustrade Finishes

Table 5. NISTIR 6389 proposed level 4 for the UNIFORMAT-II Classification of Buildings (cont.)

C3010 Wall Finishes	C3011 Wall Finishes to Inside Exterior Walls C3012 Wall Finishes to Interior Walls C3013 Column Finishes	D2090 Other Plumbing Systems	D2091 Gas Distribution D2092 Acid Waste Systems D2093 Interceptors D2094 Pool Piping and Equipment D2095 Decorative Fountain Piping Devices D2099 Other Piping Systems
C3020 Floor Finishes	C3021 Floor Toppings C3022 Traffic Membranes C3023 Hardeners and Sealers C3024 Flooring C3025 Carpeting C3026 Bases, Curbs and Trim C3027 Access Pedastal Flooring	D3010 Energy Supply	D3011 Oil Supply System D3012 Gas Supply System D3013 Coal Supply System D3014 Steam Supply System D3015 Hot Water Supply System D3016 Solar Energy System D3017 Wind Energy System
C3030 Ceiling Finishes	C3031 Ceiling Finishes C3032 Suspended Ceilings C3033 Other Ceilings	D3020 Heat Generating Systems	D3021 Boilers D3022 Boiler Room Piping & Specialties D3023 Auxiliary Equipment D3024 Insulation
D1010 Elevators & Lifts	D1011 Passenger Elevators D1012 Freight Elevators D1013 Lifts	D3030 Cooling Generating Systems	D3031 Chilled Water Systems D3032 Direct Expansion Systems
D1020 Escalators & Moving Walks	D1021 Escalators D1022 Moving Walks	D3040 Distribution Systems	D3041 Air Distribution Systems D3042 Exhaust Ventilation Systems D3043 Steam Distribution Systems D3044 Hot Water Distribution D3045 Chilled Water Distribution D3046 Change-over Distribution System D3047 Glycol Distribution Systems
D1090 Other Conveying Systems	D1091 Dumbwaiters D1092 Pneumatic Tube Systems D1093 Hoists & Cranes D1094 Conveyors D1095 Chutes D1096 Turntables D1097 Baggage Handling & Loading Systems D1098 Transportation Systems	D3050 Terminal & Package Units	D3051 Terminal Self-Contained Units D3052 Package Units
D2010 Plumbing Fixtures	D2011 Water Closets D2012 Urinals D2013 Lavatories D2014 Sinks D2015 Bathtubs D2016 Wash Fountains D2017 Showers D2018 Drinking Fountains and Coolers D2019 Bidets and Other Plumbing Fixtures	D3060 Controls & Instrumentation	D3061 Heating Generating Systems D3062 Cooling Generating Systems D3063 Heating/Cooling Air Handling Units D3064 Exhaust & Ventilating Systems D3065 Hoods and Exhaust Systems D3066 Terminal Devices D3067 Energy Monitoring & Control D3068 Building Automation Systems D3069 Other Controls & Instrumentation
D2020 Domestic Water Distribution	D2021 Cold Water Service D2022 Hot Water Service D2023 Domestic Water Supply Equipment	D3070 Systems Testing & Balancing	D3071 Piping System Testing & Balancing D3072 Air Systems Testing & Balancing D3073 HVAC Commissioning D3079 Other Systems Testing and Balancing
D2030 Sanitary Waste	D2031 Waste Piping D2032 Vent Piping D2033 Floor Drains D2034 Sanitary Waste Equipment D2035 Pipe Insulation	D3090 Other HVAC Systems & Equipment	D3091 Special Cooling Systems & Devices D3092 Special Humidity Control D3093 Dust & Fume Collectors D3094 Air Curtains D3095 Air Purifiers D3096 Paint Spray Booth Ventilation D3097 General Construction Items (HVAC)
D2040 Rain Water Drainage	D2041 Pipe & Fittings D2042 Roof Drains D2043 Rainwater Drainage Equipment D2044 Pipe Insulation	D4010 Sprinklers	D4011 Sprinkler Water Supply D4012 Sprinkler Pumping Equipment D4013 Dry Sprinkler System

Table 5. NISTIR 6389 proposed level 4 for the UNIFORMAT-II Classification of Buildings (cont.)

D4020 Standpipes	D4021 Standpipe Water Supply D4022 Pumping Equipment D4023 Standpipe Equipment D4024 Fire Hose Equipment	E2010 Fixed Furnishings	E2011 Fixed Artwork E2012 Fixed Casework E2013 Blinds and Other Window Treatment E2014 Fixed Floor Grilles and Mats E2015 Fixed Multiple Seating E2016 Fixed Interior Landscaping
D4030 Fire Protection Specialties	D4031 Fire Extinguishers D4032 Fire Extinguisher Cabinets	E2020 Movable Furnishings	E2021 Movable Artwork E2022 Furniture & Accessories E2023 Movable Rugs and Mats E2024 Movable Interior Landscaping
D4090 Other Fire Protection Systems	D4091 Carbon Dioxide Systems D4092 Foam Generating Equipment D4093 Clean Agent Systems D4094 Dry Chemical System D4095 Hood & Duct Fire Protection	F1010 Special Structures	F1011 Air Supported Structures F1012 Pre-engineered Structures F1013 Other Special Structures
D5010 Electrical Service & Distribution	D5011 High Tension Service & Dist. D5012 Low Tension Service & Dist.	F1020 Integrated Construction	F1021 Integrated Assemblies F1022 Special Purpose Rooms F1023 Other Integrated Construction
D5020 Lighting & Branch Wiring	D5021 Branch Wiring Devices D5022 Lighting Equipment	F1030 Special Construction Systems	F1031 Sound, Vibration & Seismic Const. F1032 Radiation Protection F1033 Special Security Systems F1034 Vaults F1039 Other Special Construction Systems
D5030 Communications & Security	D5031 Public Address & Music Systems D5032 Intercommunication & Paging Syst. D5033 Telephone Systems D5034 Call Systems D5035 Television Systems D5036 Clock and Program Systems D5037 Fire Alarm Systems D5038 Security and Detection Systems D5039 Local Area Networks	F1040 Special Facilities	F1041 Aquatic Facilities F1042 Ice Rinks F1043 Site Constructed Incinerators F1044 Kennels & Animal Shelters F1045 Liquid & Gas Storage Tanks F1049 Other Special Facilities
D5090 Other Electrical System	D5091 Grounding Systems D5092 Emergency Light & Power Systems D5093 Floor Raceway Systems D5094 Other Special Systems & Devices D5095 General Construction Items (Elect.)	F1050 Special Controls & Instrumentation	F1051 Recording Instrumentation F1052 Building Automation System F1059 Other Special Controls & Instrumentation
E1010 Commercial Equipment	E1011 Security & Vault Equipment E1012 Teller and Service Equipment E1013 Registration Equipment E1014 Checkroom Equipment E1015 Mercantile Equipment E1016 Laundry & Dry Cleaning Equipment E1017 Vending Equipment E1018 Office Equipment	F2010 Building Elements Demolition	F2011 Building Interior Demolition F2012 Building Exterior Demolition
E1020 Institutional Equipment	E1021 Ecclesiastical Equipment E1022 Library Equipment E1023 Theater & Stage Equipment E1024 Instrumental Equipment E1025 Audio-visual Equipment E1026 Detention Equipment E1027 Laboratory Equipment E1028 Medical Equipment E1029 Other Institutional Equipment	F2020 Hazardous Components Abatement	F2021 Removal of Hazardous Components F2022 Encapsulation of Hazardous Components
E1030 Vehicular Equipment	E1031 Vehicular Service Equipment E1032 Parking Control Equipment E1033 Loading Dock Equipment E1039 Other Vehicular Equipment	E1090 Other Equipment	E1091 Maintenance Equipment E1092 Solid Waste Handling Equipment E1093 Food Service Equipment E1094 Residential Equipment E1095 Unit Kitchens E1097 Window Washing Equipment E1099 Other Equipment
(Note E1090 moved right for convenience) →			

Construction Specifications Institute (2004). Along with UNIFORMAT-II, the MasterFormat classification system represents the second of the two major systems used by the United States construction industry for classifying building construction work. It is an organizational standard for construction specifications for materials, products, and systems in most commercial and institutional building projects in the U.S. and Canada. It has been recently expanded (MasterFormat Expansion Task Team 2003) to address rapidly expanding building technologies such as integrated automation systems and electronic safety and security systems. It has 50 basic divisions (increased from 16 of prior versions) and a six-digit numbering system. Because it is used for construction specifications, its taxonomy is clearly defined. The system is highly detailed: a complete listing of its classification scheme takes 170 pages without explanatory text. It is familiar to construction contractors and others. The fine detail presents problems. For example, it distinguishes the metal studs of interior partitions from the wallboard-partition sheathing, showing these two components in separate taxonomic groups. Certain groups do seem to represent larger assemblies, however. For example, while there are separate groups for metal framing and for gypsum wallboard sheathing of wallboard partitions, there is also a group for gypsum board assemblies. Because of these redundant assembly-level groups, the system is testable and amenable to the assessment of consequences, but is not collectively exhaustive. As with other taxonomic system that were not designed with PBEE in mind, it does not distinguish differences in seismic performance.

RS Means (2004) assembly numbering system. RS Means' primary business is research, analysis, and reporting on construction costs. Its assembly taxonomic system is therefore designed for use in construction (and repair) cost estimation. The assembly numbering system is an extension of the UNIFORMAT-II 5-digit system up to level 3, beyond which RS Means adds an additional 3-digit major classification and a final four-digit line number. Despite the detail, the taxonomic groups are testable, and much of the detail simply provides cost information about modest variations between similar assembly types. For example, RS Means provides cost information about 42 versions of drywall partition on metal stud framing. The taxonomic groups are clearly defined and collectively exhaustive, and with an important limitation discussed below, can be reasonably expected to share common fragility functions. Because of the detail and emphasis on cost, this system is highly amenable to assessing consequences. Its hierarchical structure make it collapsible. RS Means is familiar to contractors and engineers. The major limitations of this taxonomic system are fourfold: (1) its groups do not distinguish some features of seismic resistance, such as the presence of bracing in sprinkler lines or anchorage in floor-mounted electrical equipment; (2) the system is very large, occupying more than 500 pages, with much of the detail irrelevant to seismic performance; (3) to duplicate this extensive taxonomy would require copyright or other agreements that RS Means has expressed an unwillingness to arrange (Miranda 2005); and (4) to use RS Means' taxonomy would tie PBEE to a costly, single-source publication.

RS Means (2000) component numbering system. This document provides unit costs for repair and remodeling, along with greater detail than the RS Means' (2004) assembly cost manual on construction crew productivity and therefore repair duration. The numbering system is based on the familiar CSI MasterFormat, rather than UNIFORMAT-II as in the assembly-numbering system. The taxonomy is clearly defined, collectively exhaustive, and fine enough (with an important limitation noted below) to be testable, amenable to the assessment of consequences (particular because of the cost and duration data), collapsible, and have taxonomic groups that share common fragility functions. As with the RS Means assembly-numbering system, the major limitations of this taxonomic system are that its groups do not distinguish some features of seismic resistance, is very large (with most of the detail irrelevant to seismic performance), and raises issues of copyrights and high cost.

RELEVANCE OF FRAGILITY DATA FOR A NONSTRUCTURAL TAXONOMY

It is worthwhile at this point to review a sample of important fragility tests and surveys, because they highlight features that distinguish differences in seismic performance. A feature of a common damageable component that makes a material difference in damageability should be reflected in the taxonomy. It is beyond the present scope of work to perform an exhaustive literature review of the fragility of all nonstructural components, but a brief review is presented here of analytical works about key nonstructural components that commonly contribute to losses. These include investigations into the performance of nonstructural partitions by Pardoen et al. (2000), glazing by Sucuoglu and Vallabhan (1997), suspended ceilings by the present author (Porter 2000), commercial and industrial mechanical and electrical equipment by Swan and Kassawara (1998), building service equipment by Johnson et al. (1999), household property by Saeki et al. (2000), small laboratory equipment by Hutchinson (Comerio 2004), and modular office furniture by Filiatrault (1991).

Nonstructural partitions. Pardoen et al. (2000) performed racking tests of a variety of architectural wall systems with various finish materials, framing system, and fasteners. They found that stucco-wall yield displacement (associated with onset of damage) can differ from that of gypsum wallboard by a factor of 3, and from plywood and oriented strandboard by a factor of 10; hence the taxonomy must distinguish between finish materials on nonstructural walls. Gypsum wallboard of 5/8-in thickness was observed to have 60% greater ultimate drift capacity than ½-in wallboard, so wallboard thickness matters to fragility, and presumably sheathing thickness in general matters. (The authors tested nearly constant thicknesses of wood sheathing, so little can be observed from their data about the importance of wood-sheathing thickness on fragility.) Stucco-wall yield displacements differ by a factor of 2 depending on whether the connectors are furring nails or staples, so connectors matter.

Glazing. Limited racking or shake-table tests have been performed of glazing. Examples include Pantelides and Behr (1994), Behr et al. (1995) and Behr and Worrell (1998). Sucuoglu and Vallabhan (1997) present a useful theoretical examination of the fragility of window glass during earthquakes that is more generally applicable, although it is a deterministic, not probabilistic, model. Using their model, one finds that, for floating glass (i.e., with flexible support to the glass within the frame), the chief parameters affecting glazing fracture are glass width, height, and the gap between the glass and the frame, echa of which, within reasonable bounds, can increase or decrease drift capacity by at least ±50%. Smaller panes and ones with greater gaps are more rugged. Pane thickness, tensile strength and Young's modulus have more modest effect on glazing capacity, affecting drift capacity by less than 20% ±0.0015 of interstory drift ratio.

Laboratory equipment. Hutchinson performed shake-table tests of a variety of laboratory equipment, measuring permanent displacement of objects of various size and base friction, such as computers, microscopes, glassware, etc. (Comerio 2004). In the same publication, the present author analyzed the displacement results to determine the features that matter to whether the objects would slide off a countertop or shelf in an earthquake. For these common laboratory objects, two features matter most to sliding off: base friction and location. It seems likely that common restraint measures such as shelf lips also matter, but these were not tested. Base friction was divided into two groups, low (coefficient of static friction less than 0.5) and high (greater than 0.5), which essentially means that if the interface between object and counter or shelf includes rubber, then the base friction is high; otherwise, it is low. Location was divided into countertop and shelf, the material distinction being the distance the object must slide before sliding off. A third parameter—weight—does not matter for sliding off, but may matter for consequent injuries. Weight was categorized as low (less than 20 lb), medium (20-400 lb), and high (greater than 400 lb), based on the judgment of consultants who contributed to the study.

Swan and Kassawara (1998). These authors describe a database of the observed performance of 20 categories of mechanical, electrical, and plumbing equipment in commercial and industrial facilities in 25 earthquakes. The database was compiled in collaboration with the Electric Power Research Institute. The authors also present a methodology for developing fragility functions based on observed performance, as well as the derived fragility function for each category of components. (Here, the fragility functions describe the probability that the equipment will fail to operate after an earthquake, as a function of peak base acceleration.) The authors describe installation conditions that make a material difference in component fragility. This is important: for several of these categories of equipment, seismic installation condition can be described as a binary feature that can be used to define the category of equipment. That is, some components can be said either to be installed to resist earthquakes, or not installed for seismic resistance, based on the post-earthquake observation of several thousand pieces of commercial and industrial equipment. That is not to say that all nonstructural or other building components can be defined as either seismically installed or not, merely that *some* categories can.

International Code Council (2000). The International Building Code addresses nonstructural components through design requirements tailored to different component categories. Its table 1621.2 distinguishes 13 categories of architectural components or elements, each with up to three subcategories (see Table 1). Furthermore, walls and finishes are segregated by fire-resistance rating. A variety of fire-protection systems, smoke-protection system, and their components are defined. Several categories of glazing are addressed. Gypsum board, plaster, and stucco are addressed. Mechanical, electrical, and plumbing systems are addressed by other codes. There is brief discussion of elevators and conveying systems and their components.

Johnson et al. (1999). These authors offer a tool to estimate and manage the seismic reliability of equipment systems, based on a detailed examination of the system components, and using a simplified logic-tree analysis of the system. The methodology produces a "seismic score" for an overall equipment system, which relates to the annual probability of the equipment system failing to perform its required function. Individual equipment components are assessed using a set of standard, 2-page, multiple-choice forms, one for each of 37 component types. The forms allow the analyst to estimate the seismic reliability of the component, considering the type of component, the seismic hazard at the site, the location of the component within the building, and its installation conditions such as adequacy of seismic restraint and potential for interaction with other components. The scores are then used to assess the reliability of the overall equipment system. The forms offer a pre-established taxonomy of components and of common installation conditions and deficiencies. As in Swan and Kassawara, these authors have defined discrete conditions that distinguish seismically resistant equipment from otherwise. These discrete conditions can be reflected in a taxonomy that has different taxonomic groups to reflect conditions of seismic installation.

Saeki et al. (2000). These authors present data on household property loss resulting from the 1995 Kobe earthquake. The data come from 965 questionnaires returned by insurance-company employees living in the Hyogo and Osaka prefectures. Questions about household property address ownership of and damage to 10 categories of contents: six categories of durable possessions such as furniture, appliances, and electronics; and four categories of non-durables such as curtains, tableware, and clothing. The authors performed regression analyses to calculate the parameters of fragility functions for each category of household contents. The most commonly damaged components were tableware, which commonly toppled or fell to the floor at JMA intensities around 5. The most rugged components were heaters and coolers, which on average experienced damage only when subjected to JMA $\geq$ 7.25.

Table 6. Taxonomy of household contents by Saeki et al. (2000)

Type		Household property	
Durable possessions	A	Large self-standing furniture mainly used for storage (overturning)	Chests, bookshelves, and cupboards
	B	Household electrical appliances (overturning)	Electric refrigerators and washing machines
	C	Household electrical appliances (falling to the floor, toppling over)	Microwave ovens
	D	Household entertainment equipment (falling to the floor, toppling over)	Audiovisual equipment, personal computers, telecommunications equipment, and musical instruments
	E	Floor-standing furniture (crushing)	Dining tables, chairs, living room furniture, and cooking stoves
	F	Heaters and coolers (crushing, overturning)	Air conditioners and heaters
Non-durable possessions	G	Indoor accessories and miscellaneous items (crushing)	Curtains, sliding doors and screens, health and medical equipment, sporting goods, bags, shoes, *Tatami* mats, and carpets
	H	Tableware (falling to the floor, toppling over)	Tableware
	I	Home entertainment items, miscellaneous items (falling to the floor, toppling over)	Clocks, cameras, lighting fixtures, records, CDs, miscellaneous items, and toys
	J	Clothing and bedclothes (physically damaged or contaminated by glass or other foreign matter)	Clothing and bedclothes

[Masri's work for MCEER on hospital nonstructural systems. Bachman will provide.]

ASCE (2000). FEMA 356.

[Goodno, Barry ~1990, cladding, Geogia Tech]

[Factory Mutual publications. Call Pravine Malhortea at Factory Mutual – tell him that I'm working on ATC-58.]

Modular office furniture. Filiatrault (1991) reports on shake-table tests of freestanding modular office furniture. Despite tests with excitation up to 5%-damped spectral acceleration up to 1.2g, no damage or overturning of the furniture occurred. This suggests that modular office furniture is relatively rugged, and at present requires no differentiation between varieties in a nonstructural component taxonomy.

PROPOSED TAXONOMIC SYSTEM

CONCLUSIONS REGARDING EXISTING TAXONOMIES

Table 7 summarizes the taxonomies reviewed here and the degree to which they offer the desired features. Column headings list the objectives; rows list the existing systems. Each system is rated for how well it meets each objective.

Table 7. Adequacy of existing taxonomic systems to meet stated objectives.

	1. Clear definitions	2. Collectively exhaustive	3. Common fragility functions	4. Testable	5. Distinguishes performance	6. Simple	7. Assessment of consequences	8. Collapsible	9. Flexible	10. Familiar
IBC 2000; ASCE 7-05	◐	●	●	●	●	⊙	●	●	◐	⊙
HAZUS	⊙	◐	⊙	◐	●	⊙	⊙	●	●	⊙
Porter (2000)	⊙	◐	⊙	⊙	⊙	●	⊙	⊙	◐	⊙
Taghavi and Miranda (2003)	⊙	◐	●	⊙	●	●	⊙	⊙	◐	⊙
Antaki (2004)	●	●	⊙	●	⊙	◐	●	⊙	●	◐
UNIFORMAT II	◐	⊙	●	●	●	⊙	●	⊙	◐	⊙
NISTIR 6389	⊙	⊙	⊙	⊙	●	◐	⊙	⊙	◐	⊙
MasterFormat 04	⊙	◐	⊙	⊙	●	●	⊙	●	◐	⊙
RS Means assemblies	⊙	⊙	⊙	⊙	●	●	⊙	⊙	◐	⊙
RS Means components	⊙	⊙	●	⊙	●	●	⊙	⊙	◐	⊙

⊙ = true ◐ = somewhat true ● = untrue

None of the existing taxonomies examined here satisfies all ten requirements. Most are clearly defined and would be readily understandable to earthquake engineers. Only four are collectively exhaustive: UNIFORMAT-II, NISTIR 6389 (the proposed extension to UNIFORMAT-II), and the two RS Means numbering systems. Of these, the latter two are too detailed to be practical for present purposes, in addition to having copyright and cost issues that would seem to disqualify them from use. The important differences between UNIFORMAT-II and NISTIR 6389 are that the former is too brief to have common fragility functions or to be testable or amenable to the assessment of consequences.

What remains is NISTIR 6389, which is clearly defined, collectively exhaustive, has groups that are generally small enough to share common fragility functions and to be testable, is fairly simple, is explicitly designed to facilitate the assessment of consequences, appears to be readily collapsible, and should be readily understood by earthquake engineers. However, it has two important deficiencies for present purposes: it does not distinguish features that are relevant to seismic performance, and no mechanism exists for users to add new taxonomic groups as new knowledge develops.

PROPOSED TAXONOMY AND CONSEQUENCE DATABASE

These deficiencies in NISTIR 6389 could be overcome with two expedients that would probably be required for any taxonomy: First, addition of another level of detail to the classification system—here, a Level 5 below the four provided by NISTIR 6389—to reflect seismic installation conditions or other subgroups. Second, the taxonomy would have to be easily expandable and interactive, so that researchers or other future users could add subgroups within the existing taxonomy. For example, if a researcher found through experiment that by subdividing category B2021, windows, by frame gap, pane size, etc., the uncertainty on the fragility of subgroups could be reduced below that of the general category B2021, he or she could create new categories B2021.001, B2021.002, etc., name them, define their fragility functions, repair costs, etc., and make that data available to the research community.

Both expedients could be provided for by creating an online, interactive taxonomy database (with other features, described below). The database would offer queries so that users could interact with tables that list the taxonomic groups as well as their parameters of fragility, repair cost, repair duration, and other consequences such as potential for casualties and impact on post-earthquake occupiability and operability of the facility. Users would be able to look up or add records. Each record could be supplied with a pointer (URL or bibliographic citation) to the source of the parameters. Porter (2000) and Taghavi and Miranda (2003) have already developed prototypes of such a database.

Included with this manuscript is an initial draft of such a database. It contain three tables and one html data-access page. The table named “NISTIR 6389” lists the taxonomic groups through Level 4. This table includes the categories shown in Table 5, plus five new categories of structural steel elements (B1031 through B1035), four of reinforced concrete structural elements (B1041 through B1044), and one category of exterior wall finish (B4041). The layout of this table is shown in Table 8.

Table 8. Layout of database table "NISTIR 6389"

Field Name	Data Type	Description
ID	Autonumber	Table index. Table contains taxonomic groups through Level 4.
Level 1 ID	A1	UNIFORMAT-II Level 1, A through F
Level 1 description	A50	UNIFORMAT-II Level 1 description, e.g., Substructure
Level 2 ID	A3	UNIFORMAT-II Level 2, A10 through F20
Level 2 description	A50	UNIFORMAT-II Level 2 description, e.g., Foundations
Level 3 ID	A5	UNIFORMAT-II Level 3, A1010 through F2020
Level 3 description	A50	UNIFORMAT-II Level 3 description, e.g., Standard Foundations
Level 4 ID	A5	Proposed UNIFORMAT-II Level 4, A1011 through F2022
Level 4 description	A50	Proposed UNIFORMAT-II Level 4 description, e.g., Wall Foundations
Comment	A50	Comment

The second table is named "RC." It lists fragility functions and repair-cost distributions by Level-5 taxonomic group, for a modest set of component types (83 fragility functions so far). Its layout is detailed in Table 9. The third table is named "References." It lists brief citations contained in RC and shows the full bibliographic references for each brief citation. Its layout is detailed in Table 10. The data-access page is an html document that allows one to browse, edit, delete, or insert records into table "RC." An image of the data-access page is shown in Figure 4. Noteworthy features of table "RC," apparent in Figure 4, include the following:

- Brief user-friendly name for each component type, along with a detailed description.
- Table lists both NISTIR 6389 category and to RS Means category, for ease of reference for repair-cost and repair-duration information.
- Fields for fragility-function parameters, including engineering demand parameter (EDP), damage measure (DM), description of repair requirements, form of an idealized probability distribution for fragility function (five are anticipated here), and it parameters.
- Fields for repair-cost distribution and parameters, including cost year (to account for inflation) and 3-digit ZIP Code zone for which the cost is applicable (to account for variation in local construction costs).
- Citation fields for reference to source publications for fragility and cost data.
- Flags to indicate the quality of the fragility function: a field to indicate whether its basis is experimental, analytical, from earthquake experience, or judgment; another to indicate whether the fragility function has been peer reviewed.

For those categories for which the author has fragility and cost information, these data have been included as well. Fewer than 100 records currently contain fragility function and repair-cost parameters; the remainder are placeholders, showing only name, NISTIR 6389 line number, description, and EDP type. The table named "References" contains citations for all records in RC that have fragility and cost data. It would certainly be desirable to add fragility and repair-cost data compiled by Taghavi and Miranda (2003), and it might be desirable to expand the proposed database to include other consequence characteristics such as life-safety and operational consequences, as those authors did.

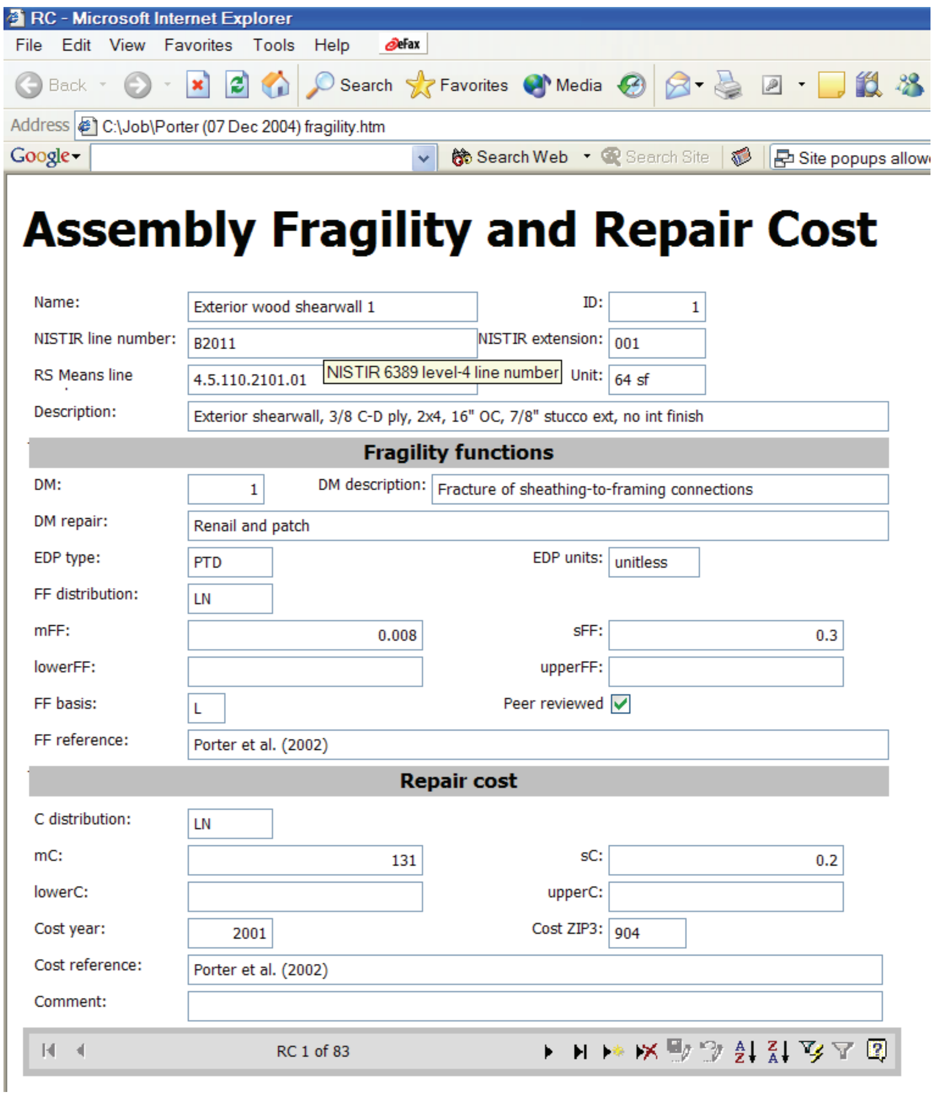

Figure 4. Data access page to taxonomy and fragility database. Note the yellow explanation that appears when the mouse pointer is placed over a data entry box.

Table 9. Layout of database table "RC"

Field Name	Data Type	Description
ID	Autonumber	Table index.Table contains parameters of fragilility functions and unit repair costs
Name	A50	A user-friendly name for the assembly type
NISTIR 6389 line number	A5	ID according to NISTIR 6389 proposed extension to UNIFORMAT-II
NISTIR 6389 extension	A3	Variant within this NISTIR 6389 category, a 3-digit serial number (001, 002, …) supplied by the user who adds the record
RS Means line number	A16	RS Means line number, either by assembly (RS Means's UniFormat extension) or component (MasterFormat extension), extended to reflect seismic condition
Description	A255	Description of assembly type
Unit	A12	Unit in which assembly is measured and at which fragility functions and cost distributions apply, e.g., ea, 64 sf, pane, etc.
DM	Integer	Damage state ID within assembly type
DM description	A75	Description of damage state
DM repair description	A50	Description of repair effort
EDP type	A4	Category of EDP most closely related to damage. Choices are peak transient drift ratio (PTD), peak diaphragm acceleration (PDA), modified Park-Ang damage index (PADI), and elastic demand-capacity ratio (DCR)
EDP units	A8	Units in which EDP is measured
Fragility function distribution	A4	Idealized form of capacity distribution (i.e., of fragility function). Choices are lognormal (LN), normal (N), beta (B), uniform (U), and exponential (E)
mFF	Single	Central value of capacity (i.e., of fragility function). For lognormal (LN) or normal (N) distribution, m = median. For beta (B) or exponential (E), m = mean. Not needed for unifirm (U) distribution.
sFF	Single	Dispersion of capacity. For LN, s = logarithmic standard deviation. For N or B, s= standard deviation. Not needed for U or E.
lowerFF	Single	Lower bound of capacity. Only for B and U. Not used for N, LN, or E.
upperFF	Single	Upper bound of capacity. Only for B and U. Not used for N, LN, or E.
Cost distribution	A4	Idealized form of unit-repair-cost distribution. Choices are lognormal (LN), normal (N), beta (B), uniform (U), and exponential (E)
mC	Single	Central value of unit cost. For LN or N distribution, m = median. For B or E distribution, m = mean. Not needed for U distribution.
sC	Single	Dispersion of unit cost. For LN distribution, s = logarithmic standard deviation. For N or B distribution, s = standard deviation. Not needed for U or E.
lowerC	Single	Lower bound of unit cost. Only for B and U distributions. Not used for N, LN, or E.
upperC	Single	Upper bound of unit cost. Only for B and U distributions. Not used for N, LN, or E.
Cost year	Integer	Reference year for cost distribution. Format is YYYY.
Cost ZIP3	A3	Reference location for cost distribution: "Avg" means national average, otherwise use 3-digit ZIP Code zone
Fragility function basis	A1	Basis for fragility function: laboratory experiment (L), analytical (A), earthquake (E), or judgment (J)
Fragility function peer reviewed	Yes/No	Fragility function has been peer reviewed?
Fragility function reference	A50	Brief citation of publication where the capacity distribution (fragility function) is presented
Cost reference	A50	Brief citation of publication of repair-cost distribution is presented
Comment	A255	Explanatory text
Added by	A4	The initials of the person who added the record
Added date	Date/Time	The date on which the record was added
Last change by	A4	The initials of the person who last changed the record
Last change date	Date/Time	The date on which the record was last modified

Table 10. Layout of database table "References"

Field Name	Data Type	Description
ID	Autonumber	Index. Table contains bibliographic references for fragility functions and cost distributions
Brief reference	A50	Citation from table "FFRC"
Full reference	Memo	Full bibliographic reference

CONCLUSIONS

A taxonomic system of some kind is required to archive and disseminate damageability and loss data for use in PBEE. A set of 10 criteria for such a taxonomy is presented; the criteria were reviewed and approved by an oversight committee of academics and professionals. Several existing taxonomic systems were reviewed, but none appears to satisfy all 10 requirements. The one that comes closest is a modest extension to the UNIFORMAT-II system, proposed in 1999 by a NIST committee, in the publication NISTIR 6389. NISTIR 6389 proposes the addition of a 4th level to the UNIFORMAT-II system, for the purpose of eliminating some ambiguities in UNIFORMAT-II and to facilitate access to existing cost data. In contrast with the next best existing taxonomic systems (RS Means' assembly and component numbering systems), NISTIR 6389 offers a manageable level of detail and it avoids potentially serious copyright and cost issues that would arise from the use of the proprietary RS Means cost manuals.

It is proposed here to use an extension of the NISTIR 6389 taxonomy for present purposes. The reason for the extension is that the NISTIR 6389 taxonomy has three important shortcomings. First, the taxonomy fails to reflect important differences in seismic installation conditions. Second, it is necessary for present purposes to provide flexibility for future development and additions by PBEE researchers and others. Finally, a few important structural taxonomic groups are not explicitly named, such as beams, columns, braces, connections, and shearwalls.

To overcome these difficulties, three enhancements to NISTIR 6389 are proposed. First, an additional 5th level of detail is added. Future users would be free to define as new research becomes available. Second, it is proposed that the taxonomy be housed within an interactive, online database that also includes fragility data, repair cost and repair-duration data, and potentially other consequences such as life safety and system and facility operability. Third, nine level-4 taxonomic groups are added to reflect the undifferentiated structural components.

A pilot database is provided here. The database is a starting point, containing the NISTIR taxonomy and a table of fragility and cost data compiled by the author over the last few years. However, the content and interactivity of the pilot database are limited. The author hopes to add fragility and cost data compiled by Taghavi and Miranda (2003). To be practical for use by others, the database will require additional coding. For example, validation rules need to be added to ensure that Level-5 taxonomic group numbers shown in the fragility and cost table are not duplicated by different contributors, and that Level-4 group numbers in the fragility and cost table are consistent with those defined in NISTIR 6389. Additional security and validation features would probably be required.

Finally, a host would have to be found, and long-term maintenance arranged. The host should be one or more durable institution such as the Applied Technology Council, the Earthquake Engineering Research Institute, the California Institute of Technology's Library system, or the UC Berkeley Earthquake Engineering Research Library. The George E Brown Network for Earthquake Engineering Simulation (NEES) would be a reasonable consideration if its life were not explicitly limited to 10 yr.

IMPORTANT TAXONOMIC GROUPS

[This section is incomplete. It is included here as a placeholder.]

Based on the foregoing literature review, it appears that the types of nonstructural components that contribute most substantially to historic losses include…

COLLAPSING THE TAXONOMY

[This section is incomplete. It is included here as a placeholder.]

This section presents the mathematics to collapse detailed component fragility and loss information into broader categories of nonstructural components….

REFERENCES

American Society of Civil Engineers, 2005, *Minimum Design Loads for Buildings and Other Structures, SEI/ASCE 7-05*, Reston, VA.

American Society of Civil Engineers (ASCE), 2000, *FEMA-356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings,* Washington, DC, 490 pp.

American Society for Testing and Materials (ASTM), 2002. *E1557-02 Standard classification for building elements and related sitework – UNIFORMAT II,* West Conshohocken, PA, 24 pp.

Antaki, G., 2004. Personal communication.

Bachman, R. E., 2004. The ATC 58 project plan for nonstructual components, *International Workshop on Performance-Based Seismic Design, Concepts and Implementation, June 28-July 1, 2004, Bled, Slovenia,* Pacific Earthquake Engineering Research Center, Richmond, CA

Beck, J.L., K.A. Porter, R. Shaikhutdinov, S. K. Au, K. Mizukoshi, M. Miyamura, H. Ishida, T. Moroi, Y. Tsukada, and M. Masuda, 2002, *Impact of Seismic Risk on Lifetime Property Values, Final Report,* Consortium of Universities for Research in Earthquake Engineering, Richmond, CA, http://resolver.caltech.edu/caltechEERL:2002.EERL-2002-04

Behr, R.A., A. Belarbi, and C.J. Culp, 1995, "Dynamic Racking Tests of Curtain Wall Glass Elements with In-Plane and Out-of-Plane Motions," *Earthquake Engineering and Structural Dynamics*, 24, J. Wiley & Sons, Inc., New York, NY, 1-14

Behr, R.A., and C.L. Worrell, 1998, "Limit States for Architectural Glass under Simulated Seismic Loadings," *Proc., Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, ATC-29-1 January 22-23, 1998, Applied Technology Council, San Francisco, Redwood City, CA, 229-240

Construction Specifications Institute (CSI), 1995, *Master List of Numbers and Titles for the Construction Industry, MP-2-1,* Alexandria, Virginia

Czarnecki, R. M., 1973. *Earthquake Damage to Tall Buildings, Structures Publication 359,* Massachusetts Institute of Technology, Cambridge, MA, 125 pp.

Federal Emergency Management Agency (FEMA), 2004. *Seismic Retrofitting of Non-Structural Elements: Lighting in the Los Angeles Unified School District*, Washington DC

Filiatrault, A., 1991, "Seismic Evaluation of Modular Office Furniture," *Earthquake Spectra*, 7 (4), 529-541

International Code Council, 2000. *International Building Code 2000,* International Conference of Building Officials, Whittier, CA, 756 pp.

Johnson, G. S., Sheppard, R. E., Quilici, M. D., Eder, S. J., and Scawthorn, C. R., 1999. *Seismic Reliability Assessment of Critical Facilities: A Handbook, Supporting Documentation, and Model Code Provisions, MCEER-99-0008*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 384 pp.

Kao, A., T.T. Soong, and A. Vender, 1999, *Nonstructural Damage Database, MCEER-99-0014,* Multidisciplinary Center for Earthquake Engineering Research, State University of New York, Buffalo, NY, 71 pp., http://mceer.buffalo.edu/publications/reports/docs/99-0014/default.asp

Kircher, C. A., Nassar, A. A., Kustu, O., and Holmes, W. T., 1997. Development of building damage functions for earthquake loss estimation, *Earthquake Spectra*, **13** (4), 663-682

Kustu, O., Miller, D. D., and Brokken, S. T., 1982. *Development of Damage Functions for Highrise Building Components*, URS/John A Blume & Associates, San Francisco, CA

Miranda, E., 2005, personal communication

(NIBS and FEMA) National Institute of Building Sciences and Federal Emergency Management Agency, 1999, *HAZUS Earthquake Loss Estimation Methodology: Technical Manual, I and II,* Federal Emergency Management Agency, Washington, DC

(NIST) National Institute of Standards and Technology, 1999. *UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis*, NISTIR 6389, Washington, D.C., 93 pp., http://www.bfrl.nist.gov/oae/publications/nistirs/6389.pdf

Pantelides, C.P. and R.A. Behr, 1994, "Dynamic In-Plane Racking Tests of Curtain Wall Glass Elements," *Earthquake Engineering and Structural Dynamics*, 23, J. Wiley & Sons, Inc., New York, NY, 211-228

Pardoen, G. C., Kazanjy, R. P., Freund, E., Hamilton, C. H. , Larsen, D., Shah, N., and Smith A., 2000. Results from the City of Los Angeles-UC Irvine shear wall test program, *Proc., 6th World Conf on Timber Engineering* http://timber.ce.wsu.edu/Resources/papers/1-1-1.pdf

Petal, M. A., 2004. *Urban Disaster Mitigation and Preparedness: the 1999 Kocaeli Earthquake,* doctoral dissertation, University of California, Los Angeles, 2004

Porter, K.A., J.L. Beck, H.A. Seligson, C.R. Scawthorn, L.T. Tobin, and T. Boyd, 2002, *Improving Loss Estimation for Woodframe Buildings,* Consortium of Universities for Research in Earthquake Engineering, Richmond, CA, 136 pp., http://resolver.caltech.edu/caltechEERL:2002.EERL-2002-01 (main report) and http://resolver.caltech.edu/caltechEERL:2002.EERL-2002-02 (appendices)

Rihal, S. S., 1982. Behavior of nonstructural building partitions during earthquakes, *Proceedings of the Seventh Symposium on Earthquake Engineering, Department of Earthquake Engineering, University of Roorke, India, November 10-12, 1982*, 267-277

RS Means, 2004. *Means Assemblies Cost Data 2004 Book, 29th Edition,* Kingston, MA, 575 pp.

RS Means, 2000. *Means Repair and Remodeling Cost Data, 21st Edition, Commercial/Residential,* Kingston, MA, 645 pp.

Saeki, T., Tsubokawa, H., and Midorikawa, S., 2000. Seismic damage evaluation of household property by using geographic information systems (GIS), *Proceedings, 12th World Conference on Earthquake Engineering, , January 30 – February 5, Auckland New Zealand,* International Association for Earthquake Engineering, paper 1968, 8 pp.

Taghavi, S., and Miranda, E., 2003. *Response Assessment of Nonstructural Building Elements,* PEER 2003/05, Pacific Earthquake Engineering Research Center, Richmond, CA